BASIN ANALYSIS AND ECONOMIC GEOLOGY OF THE NORTHERN MOUNT ISA BASIN

Volume 1 of 3

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This thesis is submitted in partial fulfilment of the degree

Doctor of Philosophy at the School of Geology,

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DECLARATION

I acknowledge that:

> The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution;
>
> To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

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THESIS TITLE: Basin analysis and economic geology of the northern Mt Isa Basin, Queensland.

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FRONTISPIECE

"Scientists still do not appear to understand sufficiently that all earth sciences must contribute evidence towards unveiling the state of our planet in earlier times, and that the truth of the matter can only be reached by combining all this evidence".

Alfred Wegener

Author's Forward

The Origin of Continents and Oceans

4th Edition

1929

ABSTRACT

The Mount Isa Basin is a new concept used to describe the area of Palaeo- to Mesoproterozoic rocks south of the Murphy Inlier and inappropriately described presently as the Mount Isa Inlier. The new basin concept presented in this thesis allows for the characterisation of basin-wide structural deformation, correlation of mineralisation with particular lithostratigraphic and seismic stratigraphic packages, and the recognition of areas with petroleum exploration potential.

The northern depositional margin of the Mount Isa Basin is the metamorphic, intrusive and volcanic complex here referred to as the Murphy Inlier (not the "Murphy Tectonic Ridge"). The eastern, southern and western boundaries of the basin are obscured by younger basins (Carpentaria, Eromanga and Georgina Basins). The Murphy Inlier rocks comprise the seismic basement to the Mount Isa Basin sequence. Evidence for the continuity of the Mount Isa Basin with the McArthur Basin to the northwest and the Willyama Block (Basin) at Broken Hill to the south is presented. These areas combined with several other areas of similar age are believed to have comprised the Carpentarian Superbasin (new term).

The application of seismic exploration within Authority to Prospect (ATP) 423P at the northern margin of the basin was critical to the recognition and definition of the Mount Isa Basin. The Mount Isa Basin is structurally analogous to the Palaeozoic Arkoma Basin of Illinois and Arkansas in southern USA but, as with all basins it contains unique characteristics, a function of its individual

development history. The Mount Isa Basin evolved in a manner similar to many well described, Phanerozoic plate tectonic driven basins. A full Wilson Cycle is recognised and a plate tectonic model proposed.

The northern Mount Isa Basin is defined as the Proterozoic basin area northwest of the Mount Gordon Fault. Deposition in the northern Mount Isa Basin began with a rift sequence of volcaniclastic sediments followed by a passive margin drift phase comprising mostly carbonate rocks. Following the rift and drift phases, major north-south compression produced east-west thrusting in the south of the basin inverting the older sequences. This compression produced an asymmetric epi- or intra-cratonic clastic dominated peripheral foreland basin provenanced in the south and thinning markedly to a stable platform area (the Murphy Inlier) in the north. The final major deformation comprised east-west compression producing north-south aligned faults that are particularly prominent at Mount Isa.

Potential field studies of the northern Mount Isa Basin, principally using magnetic data (and to a lesser extent gravity data, satellite images and aerial photographs) exhibit remarkable correlation with the reflection seismic data. The potential field data contributed significantly to the unravelling of the northern Mount Isa Basin architecture and deformation.

Structurally, the Mount Isa Basin consists of three distinct regions. From the north to the south they are the Bowthorn Block, the Riversleigh Fold Zone and the Cloncurry Orogen (new names). The **Bowthorn Block**, which is located between the Elizabeth Creek Thrust Zone and the Murphy Inlier, consists of an asymmetric wedge of volcanic, carbonate and clastic rocks. It ranges from over 10 000 m stratigraphic thickness in the south to less than 2000 m in the north. The Bowthorn Block is relatively undeformed: however, it contains a series of reverse faults trending east-west that are interpreted from seismic data to be down-to-the-north normal faults that have been reactivated as thrusts. The **Riversleigh Fold Zone** is a folded and faulted region south of the Bowthorn Block, comprising much of the area formerly referred to as the Lawn Hill Platform. The **Cloncurry Orogen** consists of the area and sequences equivalent to the former Mount Isa Orogen. The name Cloncurry Orogen clearly distinguishes this area from the wider concept of the Mount Isa Basin.

The South Nicholson Group and its probable correlatives, the Pilpah Sandstone and Quamby Conglomerate, comprise a later phase of now largely eroded deposits within the Mount Isa Basin. The name South Nicholson Basin is now outmoded as this terminology only applied to the South Nicholson Group unlike the original broader definition in Brown et al. (1968).

Cored slimhole stratigraphic and mineral wells drilled by Amoco, Esso, Elf Aquitaine and Carpentaria Exploration prior to 1986, penetrated much of the stratigraphy and intersected both minor oil and gas shows plus excellent potential source rocks. The raw data were reinterpreted and augmented with seismic stratigraphy and source rock data from resampled mineral and petroleum stratigraphic exploration wells for this study.

Since 1986, Comalco Aluminium Limited, as operator of a joint venture with Monument Resources Australia Limited and Bridge Oil Limited, recorded approximately 1000 km of reflection seismic data within the basin and drilled one conventional stratigraphic petroleum well, Beamesbrook-1. This work was the first reflection seismic and first conventional petroleum test of the northern Mount Isa Basin. When incorporated into the newly developed foreland basin and maturity models, a grass roots petroleum exploration play was recognised and this led to the present thesis.

The Mount Isa Basin was seen to contain excellent source rocks coupled with potential reservoirs and all of the other essential aspects of a conventional petroleum exploration play. This play, although high risk, was commensurate with the enormous and totally untested petroleum potential of the basin. The basin was assessed for hydrocarbons in 1992 with three conventional exploration wells, Desert Creek-1, Argyle Creek-1 and Egilabria-1. These wells also tested and confirmed the proposed basin model. No commercially viable oil or gas was encountered although evidence of its former existence was found.

In addition to the petroleum exploration, indeed as a consequence of it, the association of the extensive base metal and other mineralisation in the Mount Isa Basin with hydrocarbons could not be overlooked. A comprehensive analysis of the available data suggests a link between the migration and possible generation or destruction of hydrocarbons and metal bearing fluids. Consequently, base metal exploration based on hydrocarbon exploration concepts is probably the most effective technique in such basins. The metal-hydrocarbon-sedimentary basin-plate tectonic association (analogous to Phanerozoic models) is a compelling outcome of this work on the Palaeo- to Mesoproterozoic Mount Isa Basin. Petroleum within the Bowthorn Block was apparently destroyed by hot brines that produced many ore deposits elsewhere in the basin.

KEYWORDS

Mount Isa Basin, northern Mount Isa Basin, southern Mount Isa Basin, Mount Isa Inlier, Mount Isa Geosyncline, South Nicholson Basin, Lawn Hill Platform

Mount Isa Orogen, Bowthorn Block, Riversleigh Fold Zone, Cloncurry Orogen

lower McNamara Group, upper McNamara Group, lower Fickling Group, upper Fickling Group, South Nicholson Group

McArthur Basin, Georgetown Inlier, Georgetown Block, Broken Hill Block, Willyama Block

Wopmay Orogen, Middle East Province, Papuan Basin, Carpentaria Basin, Western Canada Basin, Alberta Foreland Basin, Eastern Venezuela Basin, Arkoma Basin, Appalachian Basin, Allegheny Basin, Illinois Basin

Sedimentary basin, rift, passive margin, foreland, play, petroleum, hydrocarbon, oil, gas, metal, lead, zinc, silver, copper, gold, iron, uranium, helium, iron, stratigraphy, reflection seismic, magnetics, gravity, Landsat, airphotos, geochemistry, plate tectonics, ore genesis, hydrodynamics, Proterozoic, Palaeoproterozoic, Mesoproterozoic

Beamesbrook-1, Egilabria-1, Desert Creek-1, Argyle Creek-1, Amoco 83-1, Amoco 83-2, Amoco 83-3, Amoco 83-4, Amoco 83-5, Amoco GRQ 81-2, Esso GCD-1, MWE Burketown-1, GSQ Lawn Hill-3, GSQ Lawn Hill-4, BMR Westmoreland-2, BHP-130, BHP-152

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ACKNOWLEDGMENTS

My thanks to:

My parents Alan and Ness McConachie and family Leticia McConachie, Sarah McConachie, Glen McConachie, who sacrificed time and inconvenience over several years to enable the production of this work and all that led up to it.

Lloyd Hamilton my senior supervisor who suggested the application and direction of the work towards a thesis and provided support and badgering in the correct carefully measured doses. My supervisors David Gust, Majorie Muir, John Wright and particularly my work colleague John Dunster with whom I have had many fruitful discussions over the years.

Bos Stainton (Exploration Manager) and Ken McDonald (General Manager) at Comalco, without whose support this work would not have been possible. Roger Meaney, Michael Barlow, Arie Schaap, Diane Carson, Max Brown, Jason Moultrie, Martin Schafer, Renee Waldrum my co-workers at Comalco were all involved with the project.

Barry Goldstein (for many good ideas), Greg Roder, and Jack Woodward of Bridge Oil plus Brian Thurley of Monument Petroleum, the joint venture partners in the project without whose support the work could not have been attempted. Keith Skipper, formerly of Bridge Oil who was very supportive of this exploration idea. John Main, Graham Broadbent (especially) and Voya Kissitch of CRAE, Kevin Tuckwell, Dennis Taylor, Doug Morris, and Kevin Lanigan of Pacific Oil and Gas, Miryam Glikson of the University of Queensland, Brian Watson of AMDEL, Peter Eadington of the CSIRO, Steve Snowdon and Tim Wilson of Australian Photogeological Consultants and Bruce Rohrlach, Michael Webb and Steve Hancock of Western Mining who all assisted with aspects of the project.

Ian Sweet, Mike Etheridge, Ken Plumb, Dave Blake and Rod Page of AGSO. Vic Wall of MIM, Martin Neudert of SEDCON, Ces Murray and Peter Jones of the DME and Paul Donovan of the DME Exploration Data Centre at Zillmere, who all provided much appreciated comments or assistance with aspects of the project.

Anna Maccheroni, Margret Hastie, and Jenny Anderson whose technical support in drafting and assembling the completed work was invaluable.

Comalco Aluminium Limited for financial support to undertake this work.

LIST OF ABBREVIATIONS

Ag	silver
AGC	automatic gain control
AGSO	Australian Geological Survey Organisation (formerly BMR)
AMDEL	Australian Mineral Development Laboratories
API	American Petroleum Institute
atm	atmospheres
ATP	Authority to Prospect
Au	gold
β	beta stretching factor (the standard measure of rift basin extension)
Ba	barium
BIF	banded iron formation
BMOD	basin modelling computer package
BMR	Bureau of Mineral Resources (now AGSO)
CDP	common depth point
CIS	Commonwealth of Independent States (Formerly USSR)
CMP	common mid point
Comalco	Comalco Aluminium Limited
CRAE	CRA Exploration
Cu	copper

DHI	direct hydrocarbon indication
DME	Department of Minerals and Energy (formerly Department of Resource Industries)
ϵ_{Nd}	epsilon Neodinium (for a detailed account of ϵ_{Nd} see Howell, 1989)
FK	frequency - wave number
FX	frequency - distance
Ga	billion (10^6) annum
GC	gas chromatograph
GSQ	Geological Survey of Queensland
HYC	Here's your chance (alternative name for McArthur River Deposit)
Hz	Hertz
IP	induced polarisation
IUGS	International Union of Geological Sciences
km	kilometre
L	litre

Ma	million annum
mg	milligram
MIM	MIM Holdings Limited
Ml	millilitre
ms	millisecond
MSFL	microspherically focussed log
ms^{-1}	metres per second
MVT	Mississippi Valley type
NaCl	sodium chloride
NMO	normal move out
OPEC	Organisation of Petroleum Exporting Countries
Pb	lead
POG	Pacific Oil and Gas
ppg	pounds per gallon
psi	pounds per square inch
P-T	Pressure-Temperature
QUT	Queensland University of Technology
SEDCON	SEDCON Sedimentary Consulting Service
SEG	Society of Exploration Geophysicists

TD	total depth
TEM	(geophys) transient electro-magnetics
TEM	(micros) transmitted electron microscopy
TM	thematic mapper
TOC	total organic carbon
TSR	tensional stress response
TTI	time temperature index
U	uranium
UV	ultra-violet
XRD	x-ray diffraction
Zn	zinc

1 INTRODUCTION

Understanding the evolution of a basin is imperative to the determination of its economic geology. To describe the evolution and economic geology of a basin, under the best of circumstances, is a large, tedious and difficult procedure. When the target is the northern Mount Isa Basin, which comprises an old and much studied, but little understood sequence of rocks, this is especially so. To cover all of the available literature thoroughly is next to impossible, but very rewarding in the light of the significant increase in knowledge of the region provided by petroleum exploration.

Basin analysis is a multidisciplinary task requiring the integrated study of seismic sequence analysis, structure at various scales, lithostratigraphy, chronostratigraphy, sedimentology, geochemistry and various potential field data, all designed to produce one coherent picture. This can be seriously and efficiently undertaken only by a team oriented approach utilising specialist consultants and contractors to cover all the pieces of the problem.

This thesis presents my contribution to this work as team leader and basin researcher for the petroleum exploration in the northern Mount Isa Basin combined with private research I undertook to fit my original studies into the "big picture" of the region. Data and interpretations contributed by other members of the Comalco project team, and the many consultants and contractors who worked on the project, are acknowledged where used in the thesis. Without the team oriented approach adopted, this work could not have been achieved either in the time available or to the breadth and depth to which the subject has been addressed.

Throughout the work presented here, data, literature review and interpretation have been kept distinct although of necessity presented jointly to maintain cohesion and readability.

1.1 BACKGROUND

Mineralisation in the Mount Isa Basin was first recognised by McKinlay while searching for Burke and Wills in 1861 (Carter et al., 1961) when he noted a specimen of rock containing copper. Initially Cloncurry, on the Cloncurry River named by Burke and Wills, was the focus of mining development in the region.

In the period that followed, the discovery of extensive base metal mineralisation at Mount Isa by Campbell Miles and others in 1923, resulted in the focussing of much exploration activity in northwest Queensland. This produced the discoveries of many world scale deposits of primarily, lead-zinc-silver and copper, along with significant gold and uranium finds. The most recent major discoveries have been of zinc-lead-silver at Century and Cannington, and copper at Ernest Henry (see Chapter 6).

Because of the economic importance of the region and the slowly dawning recognition of the vast and continuing metal exploration potential, extensive and invaluable mapping (frequently referenced in this thesis) at 1:100 000 scale has been undertaken. The work was done by the Australian Geological Survey Organisation (formerly the Bureau of Mineral Resources) in Canberra together with the Geological Survey of Queensland, a division of the Department of Minerals and Energy in Brisbane. In addition, great use was made of many drill cores preserved at the DME Exploration Data Centre at Zillmere in Brisbane.

The search for sedimentary ore and hydrocarbon deposits is very much akin to seeking needles in haystacks. Much of the history of exploration has involved large-scale rummaging in the hay until pricked (almost fortuitously) by a needle. Eventually the desire is born to know the details of each haystack, and the geographic needle distribution. Indeed, the question is then asked "Are the other haystacks the same?" So in sedimentary geology, as deeper concealed deposits are sought and the deposit trends and resource capacities of basins become desirable intelligence, basin analysis is the tool best suited to solve this general problem.

In 1986, Comalco began an extensive seismic exploration program within Authority to Prospect 373P, targeted primarily on the Carpentaria Basin. One important objective of the Comalco exploration was to locate infrabasins with hydrocarbon source rock potential. Haines and McConachie (1989) reported on a similar survey to locate infrabasins beneath the Carpentaria Basin at

Kowanyama. The result of the work west of Burketown culminated in the creation of ATP 423P that had as its objective the search for Pre-Mesozoic hydrocarbons.

Before 1986, cored slimhole stratigraphic and mineral wells drilled by Amoco, Esso, Carpentaria Exploration and several other mineral companies, penetrated much of the Pre-Mesozoic stratigraphy and intersected both minor oil and gas shows plus excellent potential source rocks. This information combined with the stratigraphic and source rock data from Beamesbrook-1 and the foreland basin model developed by the author, allowed a grass roots exploration play to be produced. This play, although high risk, was commensurate with the enormous totally untested upside petroleum potential of the basin.

This thesis is directly related to the oil search undertaken within ATP 423P.

1.2 Aim

This study was designed to explain the geology of the northern Mount Isa Basin, its definition, character, petroleum and mineral potential, and finally its evolution and formation processes. These are the keys to unlocking the full economic potential of the basin. Such an analysis in turn results in deeper understanding of earth processes related to petroleum and ore genesis. This directly benefits both prospectivity and exploration for new deposits by reducing the risks and the finding costs of resources.

If Australia is to halt its rapidly declining oil self sufficiency many alternatives will need to be considered including "grass-roots" exploration in frontier areas. To undertake this kind of exploration it is necessary to evaluate the reasons that some areas are believed to have low prospectivity for hydrocarbons. Simple lack of data and failure to understand the conditions that produce large petroleum accumulations have commonly, and needlessly, reduced exploration incentives. Hamilton (1986) provided additional background information. In the petroleum exploration industry an exploration venture is called a play. More accurately this is a perception or model of how a producible reservoir, petroleum charge system, regional top seal and trap may combine to produce petroleum accumulations at a specific stratigraphic level (Allen and Allen, 1991). The important steps in petroleum exploration are: to establish a play concept, accumulate data to develop the play, and then if it is still viable, test it. This has been the situation in the northern Mount Isa Basin, which although Proterozoic in age, appeared to contain each ingredient required for petroleum exploration success.

Frontier areas have a very high risk of failure, but the large potential rewards can justify the expenditures necessary. Generally, it is rare to find large oil and gas accumulations in areas where companies have actively searched in the past with unsuccessful results. As basins and trends are worked over, the sizes of new discoveries usually decrease. Weeks (1958) described the history of oil exploration in a large basin as very much like the history of research in most fields of investigation. A significant discovery is followed by a period of great activity along the trend. Enthusiasm runs high as long as effort is rewarded. But if success diminishes, so also does the activity, until some new idea leads to new discovery and the cycle is repeated. This situation has occurred repeatedly throughout the history of oil exploration and production. Each time revitalisation of exploration ideas results in vast additional discoveries. The industry saying that "oil is found with ideas" (Dickey, 1958) sums up the situation although it does not necessarily follow that all ideas will directly lead to petroleum discoveries. The Mount Isa Basin was one such idea.

1.3 OBJECTIVES

At the outset of this thesis study four objectives were clear although the full data set for ATP 423P which covers the northern Mount Isa Basin was not available until late 1992. The fifth objective became important as the study progressed.

1. To define and characterise the Mount Isa Basin structural and sedimentary components, and the determine its relationship to analogous basins around the world.

2. To learn the potential of the Proterozoic Mount Isa Basin to host large deposits of oil and gas (by virtue of its early hydrocarbon generation capacity and the preservation of early reservoired deposits).

3. To apply seismic analysis to characterise the Mount Isa Basin. This basin is very old, contains high velocity strata, and is a mineralised terrain where seismic analysis has not been used in the past.

4. To assess the relationship of base metals to hydrocarbon deposits. This association is evident in many basins elsewhere around the world.

5. To compare the Palaeo-Mesoproterozoic rocks at Mount Isa to a range of Phanerozoic sequences that have clearly been shown to be controlled by their plate tectonic settings. This last objective consequently provides the main thrust of this study.

Objective 1. Definition and characterisation of the Mount Isa Basin

Shrouded in "hard rock" structural and geochemical mystique, the "Mount Isa Inlier" rocks (Figure 4 of Blake, 1987; Rutland et al., 1990; see also Section 2.1) as they are commonly referred to today, represent the poorly disguised remnants of a major Proterozoic epicratonic or intracratonic, rift-drift-peripheral foreland basin (McConachie et al., 1993; Enclosure 10). The size and character of the basin is somewhat similar to, or possibly continuous with the McArthur Basin of the Northern Territory. Previously published nomenclature such as "South Nicholson Basin" and "Lawn Hill Platform" are entirely inappropriate following the seismic data acquisition and stratigraphic analysis within ATP 423P. The Lawn Hill Platform represents a pseudolithostratigraphic and structural element based upon inappropriate assumptions resulting from the confusion of a misinterpreted structural province with a basin depositional domain.

Similarly, the unnecessarily complex local structural terminologies used to describe the deformation within the Mount Isa Inlier (e.g. Stewart and Blake, 1992) are obsolete in terms of modern seismic understanding of structural styles within basins. The character and extent of fault systems identified from ATP 423P seismic data enable a basin-wide structural interpretation.

The northern Mount Isa Basin, upon which this thesis concentrates, is defined as the basin area northwest of the Mount Gordon Fault (Figure 1-1). Throughout this document, the part of the basin south and east of the Mount Gordon Fault is referred to as the southern Mount Isa Basin, but it must be remembered that the southern-most part of the basin is not yet known.

Although extensive syn- and post-depositional structural deformation occurred at Mount Isa, the northern Mount Isa Basin was largely unaffected. When all the above data is analysed and reviewed it will be proposed that the Mount Isa Basin evolved in a manner typical of Phanerozoic basins that are well documented from many regions of the world.

Objective 2. Proterozoic oil and gas plays

The Mount Isa Basin presented a unique and clearly defined opportunity (in oil exploration terms) to test a major and quite favourable play for early generated Proterozoic hydrocarbons.

Currently in the world major oil and gas production from Neoproterozoic sourced hydrocarbons occurs in Oman, the Commonwealth of Independent States (formerly the USSR) and China (see Section 5.3 Proterozoic hydrocarbons, this thesis). In Oman, Palaeozoic oil generation from Proterozoic source rocks totals 12 billion barrels. In the Russian Proterozoic sequences hydrocarbon generation may have been early, but later generative events have also occurred. The reservoirs are poor quality and little oil is produced, but large commercial gas fields are present. In China, Phanerozoic oil has almost certainly been generated from older source rock. No commercial production is known from Palaeo- to Mesoproterozoic basins in Australia although the sub-commercial Neoproterozoic Dingo Gas Field has been delineated in the Amadeus Basin (Deckelman, 1992).

Within the northern Mount Isa Basin minor oil bleeds from vugs, and gas shows from shallow mineral exploration holes, were the only physical evidence of hydrocarbons known in the area, but considering that no petroleum tests had been undertaken the petroleum potential for the basin was very encouraging.

Over the next decade as non OPEC oil production declines rapidly, the Proterozoic rocks of the world will be increasingly recognised as containing major plays for world oil production. Whoever unravels the secret of Proterozoic oil and gas occurrences will be well placed to evaluate the many unexplored Proterozoic basins of the world. Evaluation of the results in the Mount Isa Basin are very significant in this context.

Objective 3. The application of seismic analysis to old basins

The ATP 423P seismic data is the first conventional seismic data to be collected in the Mount Isa Basin. The results are described in McConachie et al. (1993). The success of the technique so far has many implications for the understanding of Proterozoic sedimentary sequences as well as the stratigraphic controls of mineral and hydrocarbon occurrences in the northern Mount Isa Basin. The definition of the rock and basin parameters in relation to the seismic acquisition details should enable the application of the seismic technique to other Proterozoic sequences and basins. The superior capacity to analyse sedimentary sequences using the seismic method together with established techniques, is aimed at providing a deeper understanding of the northern Mount Isa Basin, than the drilling, field mapping and potential field geophysical data interpretations which are all that have been used in the past. Currently AGSO is planning extensive seismic work at Mount Isa.

Objective 4. The relationship of base metals to hydrocarbons

Throughout the world the relationship between oil field brines, base metals and other mineral deposits has long been alluded to, but never fully evaluated. While the work being carried out in the northern Mount Isa Basin may not identify a specific link at the local level, on a basin scale the relationship will be tested. Analyses of the results of this work should enable this problem to be addressed in a setting where the link, until now, has been a little considered aspect of Mount Isa Basin geology. This objective has important implications for base metal mineral exploration in this region that has recently seen the discovery of the massive Century lead-zinc deposit. The Century deposit contains traces of overmature residual hydrocarbons.

Objective 5. The plate tectonic setting of the Mount Isa Basin

In North America and South Africa, plate tectonic basin settings have been recognised for both late Archaean and Proterozoic basins. Little equivalent work has been undertaken in Australia. By contrast with North America and South Africa, much evidence has been documented on the Mount Isa Basin which allows for the reconstruction of a plate tectonic model for the Palaeo- to Mesoproterozoic successions of eastern Australia. The obvious result and corresponding importance of this objective is profound in the search for mineralisation.

1.4 Scope

The objectives outlined in this thesis are important to both the hydrocarbon and minerals exploration industries. Of greater significance, however, is the irony that this work has been conducted in the Mount Isa Basin, a basin not previously understood.

The area of oil and gas exploration was confined to the northern margin of the Mount Isa Basin. To understand the structural and stratigraphic complexities as they affected the work it progressively became necessary to extend the research throughout the basin. Comprehensive analysis was then expanded to cover mineralisation and hydrocarbons, to determine the migration pathways and evaluate potential degradation of emplaced oil and gas. Extrapolation and correlation of the data to the nearby, contemporaneous McArthur Basin (at the time being explored by Pacific Oil and Gas) was a simple and logical continuation of the work. The relationship and correlation of the Mount Isa Basin with other Proterozoic sequences in eastern Australia, including the Willyama Block at Broken Hill, was also undertaken as a consequence of the initial work. This situation provided a wonderful and timely opportunity to implement the "big picture" research program carried out to provide the basis of this thesis.

This thesis is an integrated study of the northern Mount Isa Basin that of necessity includes its relationship to the Mount Isa Basin as a whole and to its surrounding contiguous and consanguineous basins. The work reported here comprises basic data, literature review and interpretations that have been integrated into a thesis with general applicability to petroleum and mineral exploration in Proterozoic rocks and basin analysis. To achieve the desired result this thesis integrates research as diverse as field mapping, thin section descriptions, chemical analyses, fluid inclusion data, seismic interpretation, drilling results and image processed potential field results into a structured, compartmentalised, format to maintain clear direction. The three major areas of the thesis are the basin analysis, the petroleum geology and the metalliferous geology.

1.5 METHODOLOGY

Petroleum exploration is, at the "grass roots" level, simply economic basin analysis. Wright (1990) applied petroleum exploration methodology very successfully to mineral exploration. The techniques of this rapidly expanding area of geology are many, but the approach is pure data acquisition and integration. In keeping with this methodology, many minor research projects, extensive literature reviews, field data acquisition programs, and discussions with many colleagues have been compiled into this thesis.

The idea of integrated sedimentary basin analysis is illustrated in two diagrams from Eidel (1991) on which the progress of the work on the Mount Isa Basin has been superimposed (Figure 1-2). This methodology allows what is currently called the "basin system approach" to be recognised and refined in the way described in Demaison and Huizinger (1989) for organic geochemical petroleum systems and Klein (1991b) for inorganic geochemical metal systems (Presented as Tables 5-2 and 6-2).

1.5.1 Induction and deduction

As with most geological situations it is very difficult to reconstruct fully the past by applying the general principle of uniformitarianism, but modern settings can provide a key to the past to test many fundamental questions that relate to the objectives of this thesis. By recognising modern types of features in the Mount Isa Basin, many objectives of this work are substantially achieved. However, to arrive at unambiguous conclusions both induction and deduction are finally required (Table 1-1).

A range of dictionaries describe these processes applied to logic as follows:

> Induction - The method or result of inferring a general principle or conclusion from particular facts; the process of reasoning by inference from particulars.
>
> Deduction - A conclusion derived from given premises; the act of subtracting; abatement; the method of deducing from premises; inference in which, granted the truth of the premises, the conclusion must be true. To derive as a conclusion, from something known or assumed; to trace the course of.

Chamberlin (1897) described the method of multiple working hypotheses. He recognised that:

> "In developing the multiple hypotheses, the effort is to bring up into view every rational explanation of the phenomenon in hand and to develop every tenable hypothesis relative to its nature, cause or origin, and to give to all of these as impartially as possible a working form and a due place in the investigation".

Gilbert (1886) had previously arrived at a similar conclusion. Gilbert considered:

> "[An investigator] is not restricted to the employment of one hypothesis at a time. There is indeed an advantage in entertaining several at once, for then it is possible to discover their mutual antagonisms and inconsistencies, and to devise crucial tests - tests which will necessarily debar some of the hypotheses from further consideration. The process of testing is then a process of elimination, at least until all but one of the hypotheses have been disproved".
>
> "In testing of hypotheses lies the prime difference between the investigator and the theorist. The one seeks diligently for the facts which may overthrow his tentative theory, the other closes his eyes to these and searches only for those which will sustain it".

Table 1-1. Induction, deduction and multiple working hypotheses

In the case of the present investigations, many data were integrated into working hypotheses and premises. Based upon these it was possible to deduce conclusions for each thesis objective.

Data and interpretations from both primary research and existing literature provided the source of the premises. The idea of the Mount Isa Basin can be thought of as a new paradigm based on the dual principles of induction and deduction. The Mount Isa Basin is not simply a new addition to the stockpile of knowledge of northwest Queensland and the northeast Northern Territory, but rather a new frame of reference for these rocks. Kuhn (1970) described the structure of scientific revolutions in terms of paradigm shifts and indeed the plate tectonic idea of the Mount Isa Basin is typical of the kind of change that he believed characterised the advance of science.

1.5.2 Techniques

Initial data acquisition in the northern Mount Isa Basin comprised a review of the lithostratigraphy by means of extensive field outcrop examination and sampling for thin section, polished section and chemical analyses. Relogging of existing drill core plus sampling and thin section description was also undertaken together with the outcrop work and various potential field studies. These comprised Landsat, magnetic, gravity, geological, geochemical, structural and geophysical data.

The predominant technique utilised in the pursuit of the northern Mount Isa Basin research was the reflection seismic method. This had not been applied to the northern Mount Isa Basin before. When combined with the deep petroleum exploration wells drilled in 1992, the data set available for analysis of the northern Mount Isa Basin was of the highest quality.

Literature research can itself be a powerful technique particularly in a much studied area like the northern Mount Isa Basin. This was utilised to reconcile all available existing geological data and fully integrate it with the ATP 423P exploration information and general field data acquisition. This large task was undertaken throughout the duration of the ATP 423P work as part of the basin analysis function to maintain the integrity of the petroleum exploration play in the basin.

Nearly all the above tasks were undertaken using a range of geological computer-based systems. The seismic interpretations were digitised into Petroseis. Auslog was used to produce core logs and graphic lithology columns. The basin was analysed using BMOD to calculate maturity profiles and analyse the burial history of the basin sequence. PEP was used to display the wireline logs and produce the composite logs. It is unlikely the work could have been satisfactorily completed using manual techniques.

1.6 Location, Geography and Access

The northern Mount Isa Basin and ATP 423P are located in northwest Queensland, in country that fringes the dry interior of the Australian continent (Figure 1-3).

The area, which in the words of a popular song is characterised by "red dust and hawks in the wind outback", comprises some of the remotest country in Queensland. The main city in the region is Mount Isa, a mining town based upon large lead-zinc-silver and copper deposits located immediately west of the township, and at Hilton some 15 km to the north.

Approximately 90 km to the east of Mount Isa is the other large population centre in the southern Mount Isa Basin, Cloncurry. This is a smaller, tourism- and rural services-based town formerly dependant on the Great Australia mine on its southern outskirts.

In the northern part of the Mount Isa Basin, the community of Burketown and the Aboriginal township of Doomadgee are the main centres, along with the tourist and camping ground at Lawn Hill Gorge. The newly discovered lead-zinc deposit at Century is the focus for the only other significant population concentration in the area.

Dry season access throughout the basin is good via dirt roads and using four wheel drive vehicles, but during the wet season the roads are often impassable. The main road connections and map sheets covering the northern part of the basin are illustrated on Figure 1-4.

1.7 Authority to Prospect 423P

Petroleum exploration in the area of ATP 423P (Figure 1-3) technically commenced in 1986 with the recognition of an infrabasin sequence beneath the Mesozoic Carpentaria Basin southwest of Burketown, situated on the southern edge of the Gulf of Carpentaria. This was followed in 1987 by a second seismic line and a conventional stratigraphic drillhole in 1988. A small regional seismic grid was then shot in 1989 to determine the extent of the still unknown infrabasin.

Following a preliminary basin analysis and seismic interpretations by the author in late 1989 a basin model was postulated. This model was presented by the author to the joint venture partners and was later tested by seismic acquisition. During 1991 a seismic program was carried out to define hydrocarbon drilling targets to be tested in 1992. These wells were the first structural petroleum drillholes in the northern Mount Isa Basin.

2 REGIONAL SETTING

From a basin analysis perspective, the regional setting is the framework that constrains the geodynamics of a basin and sets its depositional agenda. All basins evolve as they form, grow and die, and this commonly occurs at rapid geological rates. Even quite young basins show evidence of "polyhistory" and old basins show the same evolutionary features that are frozen and lithified into the rocks. The oldest rocks have been called shield areas (e.g. the Mount Isa Basin). The youngest result from breakup of the continents or from orogenic activity at the continental margins. Plate tectonics is the driving mechanism, and the regional geology is the key to general understanding and simplification of the vast amounts of data that can be extracted from a basin.

Despite the lack of understanding of the Mount Isa region due to the complex structural deformation, an extensive data set exists.

2.1 The Mount Isa Inlier

The Mount Isa Inlier is a commonly used term to describe part of the Proterozoic outcrop in northwest Queensland. A more general term within the literature is the Mount Isa Inlier and Environs. Neither of these descriptions is satisfactory for a host of reasons.

"Inlier" is a geomorphological term designed to describe old rocks of any age, surrounded by young rocks. The Mount Isa Inlier has probably existed in some form since the Palaeozoic when rocks of the Georgina Basin covered much of the area, but achieved its modern outline in the Tertiary when Eromanga and Carpentaria Basin rocks were uplifted and eroded to expose the old Proterozoic sequence.

The Mount Isa Inlier has included rocks as far north as the Murphy Inlier (Blake, 1987, Figure 4), but this fails the most basic definition of an inlier. The Mount Isa Inlier (Rutland, 1981) is a true inlier, but not a geological entity. The South Nicholson Group rocks can now be shown to comprise a younger part of the same sequence and rocks equivalent in age to the Mount Isa Inlier can now be traced to outcrop further to the north.

Therefore, the Mount Isa Inlier is an interesting geomorphological feature with no relevance to the Mount Isa Basin, other than it provides the largest continuous exposure of the sequence, and may in an almost irrelevant way show some very mild latest stage deformation of the basin.

2.2 The Proterozoic Time Scale

Various time scales (including the IUGS classification) have been applied to the Proterozoic as shown in Figure 2-1 from Plumb (1990). The scale used in this thesis is the IUGS classification. The span of the Mount Isa Basin is about 1800 Ma to 1580 Ma (Figure 3-10).

2.3 Regional data distribution

Excellent data sets exist throughout the Mount Isa region in the form of topographic and geological maps at 1:250 000 and 1:100 000 scales. Various regional geological mapping programs have been undertaken in the study area (Ahmad and Wygralak, 1989; Hutton and Wilson, 1984; Sweet, 1984; Sweet et al., 1981; Grimes and Sweet, 1979; Roberts et al., 1963; Smith and Roberts, 1963). AGSO published map sheets of the Constance Range Region and the Lawn Hill Region were not accompanied by explanatory notes. The key to published geological maps is presented in Figure 2-2. Magnetic and gravity data sets comprise mainly 1:250 000 scale sheets, but much of this is available digitally and forms an excellent base for enhanced image processing. Landsat TM data coverage of the region is complete and shows clear resolution to 1:100 000 scale. Various enhancements are also possible.

Work on this thesis utilised all of the above data sets at a range of scales. The major part of the work concentrated on the northern Mount Isa Basin where images at 1:100 000 scale were mostly used, but also looked at the big picture of the whole of the exposed basin at scales up to 1:5 000 000.

Extensive mineral exploration work has been undertaken throughout the Mount Isa Basin. Most of the published mineral data relates to relatively confined work within Authorities to Prospect that unlike the oil industry, are totally unrelated to basin scales. The recently produced AGSO Metallogenic Atlas of the Mount Isa Mineral Province attempts to address this problem. At the time of writing, the Mount Isa Basin is the focus of intense exploration activity related to the recent world class discoveries of Century and Cannington (Main, 1991; Australian Newspaper, 1992).

Previous petroleum exploration in the area (Dorrins et al., 1983) although regional in nature, did not come to grips with the basin architecture, but concentrated mainly on lithofacies analysis by using cored stratigraphic drilling. Only the northern part of the basin has ever seriously been considered prospective for oil or gas and data collection has been concentrated there.

2.4 PHYSIOGRAPHY

The Mount Isa Basin comprises sequences of hard, well lithified sedimentary rocks. Volcaniclastic, carbonate and clastic packages are present. Structural deformation and regional metamorphic grades within the basin sequence increase to the southeast and south. Contact aureoles are present where later intrusions have penetrated the basin. Although these geological features affect the physiography, the extent of the regional variation is not dramatic.

The topographic elevation of the basin surface ranges between 60 and 550 m above sea level. The highest point is Mount Guide in the southwest. Typically the average elevation is about 100 m. The basin tends to be elevated relative to the surrounding country rocks due to both the indurated character of the Mount Isa Basin sedimentary rocks and the nature of the lithofacies present. For example, where the rocks of the Carpentaria and Eromanga Basins onlap the Proterozoic, differential erosion has resulted in low ragged hills, piercing as it were, an ocean of fine grained, shallow marine Jurassic-Cretaceous rocks commonly called either the Western Queensland Plains or the Gulf Savanah (Plate 1, a and b). The Mesozoic subsidences that produced the Eromanga and Carpentaria Basins were centred over the Cooper Basin in the south and the Carpentaria Depression (McConachie et al., 1990) west of Weipa in the north. This created a regional divide called the Euroka Arch (or Narrows - it is doubtful that this was an arch in the Jurassic). The Euroka Arch is a drainage divide today and small clastic Proterozoic outcrops are exposed along it. They are known as Mount Fort Bowen, Mount Brown and Mount Little. The later Mesozoic subsidence in the Eromanga and Carpentaria Basins appears to have warped the Proterozoic outcrop of the Mount Isa Basin producing a low raged divide (Plate 1, c and d) separating streams flowing north to the Gulf of Carpentaria and south to the Lake Eyre drainage system.

By contrast the Cambrian carbonates of the Georgina Basin to the west of Mount Isa, form the flat lying but elevated and dissected Barkly Tableland. To the north, the metamorphic, volcanic and intrusive rocks of the Murphy Inlier that are significantly older than the Mount Isa Basin, form a regional topographic low (Plate 2, a). Where the Mount Isa Basin laps on to the inlier, the indurated clastic and volcanic rocks form rugged highlands and scarps relative to the easily weathered rocks (particularly the intrusions) of the inlier. On the McArthur Basin side of the Murphy Inlier the same situation applies with the aptly named China Wall being a resistant large-scale hogback or jump-up of indurated dip slope quartz-rich clastic formations.

2.5 Regional Geology and Basin Tectonic Setting

The Mount Isa Basin is located in northeastern central Australia as shown in Figure 2-4. It is a significant geological province at a continental scale. AGSO has undertaken two major regional syntheses of the data in the Mount Isa region. The first was by Carter et al. (1961) and the most recent by Blake (1987). Each concentrated on the area around Mount Isa, but also considered the regional picture. The 1:500 000 scale regional map produced by Blake op cit. is outlined in Figure 2-2 and ties together the 1:100 000 scale geological mapping in the region.

The following diagram from Vischer (1990) illustrates the distribution of unconformities in both area and time (Figure 2-3). Each type of unconformity described is believed to be represented in the Mount Isa Basin. Thus events on a scale of 100's of millions of years and 100's of millions of square kilometres

(10 000 x 10 000 km) are interspersed with local events covering 1000's of years and 100's of square kilometres (10 x 10 km).

Although structurally complex, the southern Mount Isa Basin is quite well exposed at the surface (Plate 2, b, c and d) and has been extensively studied from shallow mineral and stratigraphic drillholes. Much of the regional geology in the south is well known, if a little confused. For example, very many stratigraphic units have been defined as separate entities, but it is unlikely this is valid. The total lithostratigraphic thicknesses for the individual formations defined in the eastern and western fold belt of Blake (1987) and reported by him, added up to more than 40 km in each case. This thickness is highly unlikely as the regional metamorphic burial depths in the areas suggest a maximum of only 15 km. As basement rocks crop out in the area it is probable that the full stratigraphy is exposed at the surface, but disrupted due to fault repetition and inevitable facies variations.

The northern Mount Isa Basin was not as severely deformed and therefore has less stratigraphy exposed by outcrop than the southern part of the basin. Between Elizabeth Creek and the Mount Gordon Fault, moderate exposure of the full stratigraphic sequence occurs where faults and folds disrupt the basin. North of Elizabeth Creek there is poor outcrop of the full sequence except immediately south of the Murphy Inlier at the northern basin edge.

The relationship of the Mount Isa Basin to the other features of similar age is discussed in Chapter 3, Section 3.4.4. Several models have been suggested for the tectonic setting of the area referred to in this thesis as the Mount Isa Basin and these were reviewed by Blake (1987). Two end-member models were considered in detail, namely intracratonic and continental margin settings. As will be demonstrated later, at different times in the Wilson Cycle, each is applicable.

It is difficult and perhaps impossible to place the Mount Isa Basin within either the North Australian or Central Australian Orogenic Provinces and it is possible that these ideas are rendered obsolete. Rutland (1981) described three chelogenic cycles that have established the Australian Plate as we see it today. These are the Archaean cycle corresponding to the West Australian Orogenic Province, the Palaeo- to Mesoproterozoic cycle including both the North Australian and Central Australian Orogenic Provinces and the late Precambrian to Phanerozoic cycle of the Tasman Orogenic Province. In Rutland's scheme which avoids geographic problems, the Mount Isa Basin is readily placed within the Palaeo- to Mesoproterozoic chelogenic cycle.

To ensure clarity several descriptive terms are defined here from Bates and Jackson (1987).

Basin (Sedimentary or Structural) - A low area in the earths crust, of tectonic origin, in which sediments have accumulated. Such basins were low areas at the time of sedimentation but are not necessarily so today.
Inlier - An area or group of rocks (completely) surrounded by rocks of younger age, e.g. an eroded anticlinal crest.
Foreland - A stable area marginal to an orogenic belt, toward which the rocks of the belt were thrust or overfolded.
Foredeep / Foreland basin - These terms are both used to describe an elongate depression of the crust bordering an orogenic belt. The term foreland basin was introduced by Dickinson (1974).
Geosyncline - A mobile downwarping of the crust of the Earth, either elongate or basin-like, measured in scores (20's) of kilometres, in which sedimentary and volcanic rocks accumulate to thicknesses of thousands of meters. A geosyncline may form in part of a tectonic cycle in which orogeny follows. The idea was proposed by Hall in 1859, and the term was applied by Dana in 1873. An orthogeosyncline is located between continental and oceanic cratons, containing both volcanic and highly faulted (eugeosynclinal) and non-volcanic, weakly deformed (miogeosynclinal) belts.
Rift - A long, narrow continental trough that is bounded by normal faults; a graben of regional extent. It marks a zone along which the entire thickness of the lithosphere has ruptured under extension.
Orogeny - Literally, the process of formation of mountains. By present geological usage, orogeny is the process by which structures within fold-belt mountainous areas were formed, including thrusting, folding, and faulting in the outer and higher layers, and plastic folding, metamorphism, and plutonism in the inner and deeper layers. Only in the very youngest late Cenozoic mountains is there any evident causal relation between rock structure and surface landscape. Little such evidence is available for the early Cenozoic, still less for the Mesozoic and Palaeozoic, and virtually none for the Precambrian - yet all the deformational structures are very much alike, whatever their age, and are appropriately considered as products of orogeny.
Orogen / Orogenic belt - A linear or arcuate region that has been subjected to folding and other deformation during an orogenic cycle.

Table 2-1. Definitions of terms associated with basins and sequences (from Bates and Jackson, 1987)

2.6 PROTEROZOIC SETTING

Walter (1992b) and Stanley (1986) briefly reviewed the characteristics of the Proterozoic Earth. Based upon their generalised descriptions it is possible to provide a revealing global context for the Proterozoic of the Mount Isa Basin. Figure 2-5 illustrates the span of the Mount Isa Basin compared to biological and geological evolution of the planet. Figure 2-6 shows the explosion in stromatolite species numbers during Mount Isa Basin time.

2.6.1 Tectonics

The Proterozoic Aeon that succeeded the Archaean at 2.5 Ga, was in many ways more like the subsequent Phanerozoic Era (Stanley, 1986). Large cratons first began to form from about the late Archaean, and their persistence through the Proterozoic Era produced an extensive record of deposition in many sedimentary basins around the world. Orogenic processes similar to modern basin-forming events laid down many sedimentary sequences that remain unmetamorphosed today. Although the style of plate tectonics may have been dominated by A-type subduction (Meissner, 1986) Phanerozoic style basins were produced.

Miall (1984) summarised the evidence for basin models in the Proterozoic. The bulk of the evidence supports the emergence of modern plate tectonics before the Mesoproterozoic (see Miall, 1986, Figure 9.77, p452). Miall described Archaean greenstone belt cratonic schemes as a compromise reminiscent of the "fixist" style of geosynclinal theory that relies on simplified cross sections. By contrast, Phanerozoic plate tectonics builds orogens by unique combinations of macroplate and microplate tectonics, with orthogonal, oblique and strike-slip convergence and diachronous suturing. The pieces are simply not like a jig-saw puzzle with a unique solution but more akin to a Leggo set - a kit of parts that can be put together in an almost infinite number of ways. Syndepositional complexity on the scale of the Cordilleran, Appalachian and Alpine belts is a problem to be expected in the analysis of Precambrian plate tectonic regimes. An excellent example of Phanerozoic complexity is provided in Figure 1 of Kruger and Keller (1986).

2.6.2 Atmosphere

The Earth's primitive atmosphere, which formed by the degassing of the planet, probably contained little or no free oxygen. It is not known precisely when atmospheric oxygen reached its present level, but it was probably about 2 Ga, early in Proterozoic time. Eriksson and Truswell (1978) and Stanley (1986) reviewed atmospheric evolution in the Precambrian. Stanley noted the following evidence that low levels of atmospheric oxygen existed until Proterozoic time:

1. The presence of an early anoxic atmosphere is suggested by the development of anaerobic life that requires such conditions. Indeed the chemical reactions that yield amino acids from simpler compounds in the laboratory are inhibited by even smaller amounts of oxygen than in the earth's atmosphere today.

2. The oxidation states of uranium and iron minerals are also supportive of an Archaean-Proterozoic transition from an anoxic to oxidising conditions.

Both uraninite and pyrite are relatively abundant in buried nonmarine and shallow marine siliciclastic deposits older than 2.0 Ga and rare in younger rocks. Banded iron formations are abundant in rocks older than 1.8 Ga. Conversely, red beds are not commonly observed in Archaean sequences such as the largely non-marine Huronian and Witwatersrand strata, but common in Proterozoic and younger rocks. Red beds and chamositic, oolitic iron ores occur in the northern Mount Isa Basin.

3. The presence of photosynthetic prokaryotes at 3.5 Ga suggests oxygen liberation began in the late Archaean. Filling of oxygen sinks, principally by sulphur and iron oxidation, would then have commenced (Cloud, 1972; McLennan, 1980). Initially, until 2.2-2.3 Ga, few stromatolitic algae appear to have existed possibly due to the lack of atmospheric oxygen (Cloud, 1980). Both the lack of large continental shelves and the lack of nutrients that upwell today from the deep ocean basins may have inhibited large scale photosynthesis and oxygen production.

4. The widespread volcanism that seems to have characterised the hot Archaean earth may also have impeded the accumulation of atmospheric oxygen at this time e.g. carbon monoxide is rapidly oxidised to carbon dioxide.

The criteria used above to decide the anoxic state of the primitive Earth's atmosphere, were reviewed by Windley et al. (1984) and found inconclusive. They suggested that there was no significant evidence that an anoxic atmosphere had played a major role in metallogenesis. Whatever the result, atmospheric conditions during evolution of the Mount Isa Basin appear to have been relatively oxygen-rich.

2.6.3 Life

Fossil evidence of life is widespread throughout the Proterozoic sequences of the world including the Mount Isa Basin (Plate 3, a and b). Both Preiss (1987) and Glaessner and Walter (1981) provided useful overviews of Australian Precambrian palaeobiology. The important events can be summarised based on the descriptions of Preiss (1987) and other authors.

3500 Ma

The age of the oldest stromatolites and prokaryote microfossils in some of the oldest sedimentary rocks that are well preserved.

Proterozoic rocks contain stromatolites of many different shapes some of which form reef-like structures (Schopf, 1992). Walter (1970) provided a comprehensive account of stromatolites and the Australian Precambrian, however the use of these sedimentary structures as "fossils" for stratigraphic correlation is difficult because filamentous blue-green algae of a single type often produce stromatolites of different shapes in different environments (Stanley, 1986). Logan et al. (1964) described stromatolites as a complex of filamentous and unicellular green (Chlorophyta) and blue-green (Cyanophyta) algae. They also observed the environmental control on their structures in modern examples from Shark Bay in Western Australia.

3500 to 2000 Ma

Stromatolites were abundant from 2200-2300 Ma.

Prokaryotes have existed since at least 3500 Ma with some producing oxygen by photosynthesis. Additionally some cyanobacteria are able to carry out anoxygenic photosynthesis under reducing anaerobic conditions (Glikson and Taylor, 1986). Slow diversification of cyanobacteria probably occurred throughout the period, with oxygen possibly absorbed by oxygen sinks.

2000 to 1400 Ma

Proliferation of prokaryotes was accompanied by the probable origin of the eukaryotes.

Dr. M. Glikson pers. comm. (1991) considered the bright yellow fluorescence and morphological character of the organic matter from the sedimentary rocks of the McArthur and Mount Isa Basins to be good evidence of early eukaryote, extant *Botryococcus* (unicellular green alga) remains. These algae are known to occur in freshwater, brackish and marine environments. Cyanobacteria or blue-green algae do not produce the same bright yellow fluorescence as they do not contain large amounts of precursor oil within their structures, although methanogenic species are known.

Both Muir (1976) and Peat et al. (1978) made important contributions to the study of microfossils in the 2000 to 1400 Ma period. Muir (1976) described multicellular structures that apparently show cellular differentiation from the Amelia Dolomite of the McArthur Basin. Peat et al. (1978) described the difficulties of recognising pro- or eukaryotic affinities of organic walled microfossils from the Roper Group of the McArthur Basin including many acritarch-like spheroids, some of which were large (more than 200 µm). It is possible that early prokaryotes were much more morphologically variable than living ones, and that they were more abundant in the absence of eukaryotic competitors. Based upon this and other difficulties, Peat et al. (op. cit.) concluded that it is clear there is no way of proving conclusively that the Roper Group microfossils are pro- or eukaryotic. However, the occurrence of single large spheres within membranes that open by median splits, and the probable development of sheets of cells within membranes do make a eukaryotic origin most likely.

Stanley (1986) noted that modern spherical algae with diameters exceeding 60 µm are invariably eukaryotic. In the recent major study on the Proterozoic biosphere, Schopf (1992) concluded that eukaryotic algae evolved at around 1800 Ma, at the same time as the earliest deposition within the Mount Isa Basin.

1400 to 700 Ma

Diversification of eukaryotes occurred, and perhaps the origin of metazoa.

The oldest known commercial oil and gas accumulations are contained in rocks of this age.

700 to 600 Ma

Appearance of metazoa capable of fossilisation before the explosion of life forms capable of fossilisation at the beginning of the Palaeozoic.

The only macroscopic evidence of life in the Mount Isa Basin is stromatolites, it must be noted that these constitute poor source rocks relative to the abundant oil capacity of the extant eukaryotic algae. Fortunately the Mount Isa Basin contains abundant evidence of both immature alginite source rock (Plate 2, d) and overmature high TOC fine grained kerogen-rich rocks (Plate 2, c) suggesting the possibility that significant oil accumulations could have formed in the basin.

3 BASIN ANALYSIS - THE NORTHERN MOUNT ISA BASIN

3.1 PRINCIPLES OF BASIN ANALYSIS

Basin analysis is the integrated study of basins as geodynamical entities (Allen and Allen, 1991). Sedimentary basins contain almost all the world's known oil, plus many major mineral deposits. By virtue of the depositional processes by which they form, sedimentary basins contain the stratigraphic record of the Earth's history and evolution. Basins of different ages are important stepping stones in unravelling the processes and stages in the development of the Earth. Proterozoic rocks are no exceptions in this scheme.

Sedimentary basins are regions of prolonged subsidence that are filled with sediments that become lithified into sedimentary rocks. Therefore, the sedimentary rocks at Mount Isa attest to the existence of a sedimentary basin of some kind. Even when regionally metamorphosed by geothermal gradients in deep sedimentary piles, metasedimentary rocks bear relationships to their sedimentary basin origins. Not until anatexis and final incorporation back into the asthenosphere (which does not occur in the case of continental crust), or complete orogenesis and erosion, can sedimentary basins be truly considered to have completed their birth-death cycle.

To evaluate a sedimentary basin many regional data sets must be studied, including modern, image processed potential field information.

3.2 POTENTIAL FIELD STUDIES

Landsat and aerial photographs, gravity and magnetic data all provide an opportunity to differentiate and characterise major lithostratigraphic units in areas of Proterozoic basin outcrop. McConachie (1985) undertook a similar study of the Georgetown, Yambo and Coen areas.

Landsat TM images within the northern Mount Isa Basin were available in several formats (both slides and prints were used) and at a variety of scales down to 1: 50 000.

Aerial photographs were obtained at 1:50 000 scale in colour and 1:90 000 black and white RC9's. Both were used for field mapping and structural interpretations.

Potential field studies of the northern Mount Isa Basin (magnetics, and to a lesser extent gravity, Landsat and aerial photographs) commonly exhibit remarkable correlation with the reflection seismic data, and these contributed significantly to the unravelling of the basin architecture. Potential field data were also used extensively in the early phase of exploration in ATP 423P. Greatest exploration value was obtained from processed and enhanced images to define the extent, character and structuring of the basin sequence.

The northern Mount Isa Basin does not produce a clear gravity response. The magnetic expression of the basal volcanic rocks in the sequence, however, does enable the basin margin to be accurately identified even where overlain by younger Carpentaria Basin rocks. Landsat data were used to locate faults and surface structures within the region. Seismic data shows good correlation with the magnetic definition of the basin margin.

3.2.1 Landsat TM and aerial photography

Landsat TM images within the northern Mount Isa Basin were processed in the first instance to highlight structural details. These initial scenes were obtained as slides while later scenes showing the Comalco seismic lines were obtained as 1:100 000 scale prints. The 1:100 000 scale Landsat TM print imagery used in the current basin analysis was displayed as 7-4-1, R-G-B images. The main advantage of this composite is better colour separation with corresponding enhanced detail. The second important point is that some useful mineral discrimination is enabled with this display combination. Haematite-rich rock and soil is red while quartzites appear blue to blue-green. Limestones show as pale blue or lavender areas. Fire scars, particularly recent ones, also appear red and must be carefully distinguished from haematite-rich areas. The details of the Landsat TM spectral responses are presented and discussed in depth for the HYC (McArthur River) deposit by CSIRO (1988). A Landsat TM scene is presented in Enclosure 1.

Landsat images clearly show fault and fracture trends both within the basin and over the exposed basement to the north (Enclosure 1). Much of the roll-over structuring within this basin (although closed independent of faulting) is associated with normal and thrust fault movement at depth. Aerial photographs provide the detail of the small scale structures and the bed contacts. A detailed analysis of the Connolly Valley structure using corrected air photo data superimposed on the same scale landsat scene provides a convincing display of this "sheep herder" anticline (Figure 3-1a and b).

The major structure within the northern Mount Isa Basin is the Elizabeth Creek Thrust (Enclosure 2; Regional fault patterns, below) that separates the Riversleigh Fold Zone and the Bowthorn Block. The Elizabeth Creek Thrust can be traced clearly on Landsat TM scenes and is typical of sled-runner thrust fronts as described by Prost (1990) and Edwards (1992).

Basin Architecture

ATP 423P seismic data is shown in detail on Enclosure 2. The seismic interpretation initially showed the asymmetric foreland nature of the Mount Isa Basin sequence. Field observations of palaeocurrent directions confirmed a predominantly northerly direction of sediment transport supporting the seismic interpretation of provenance along the southern flank of the basin.

The extent of the thrusting and deformation along the southern flank of the Mount Isa Basin is difficult to assess without seismic coverage, however the punctuated nature of the South Nicholson Group with McNamara Group rocks protruding through, implies substantial sub-surface deformation. Because significant angular unconformities are present, episodic movement must have been occurring synchronous with basin development. This suggests a complex to deformed foreland basin model of the type proposed by Lucci (1986) for the northern Apennines with possibly punctuated thrusting in the south. In similar systems in the eastern Pyrenees studied by Puigdefabregas et al. (1986) thrust sheets have controlled the main depositional systems, with the foreland basin deposits progressively incorporated into the younger thrust sheets.

Along the northern margin of the Mount Isa Basin, field outcrop inspection revealed a paraconformity to disconformity compared to the steep angular unconformity at the base of the South Nicholson Group throughout the area south of the Elizabeth Creek Thrust. This suggested that the basal volcanic rocks, upper and lower McNamara, upper and lower Fickling, and South Nicholson Groups comprise a single basin regime punctuated by foreland structuring along the southern flank during the late phase of basin development. Importantly, the seismic data from the basin indicated no observable unconformity at the base of the South Nicholson Group in contrast to the outcrop information. The outcrop unconformity appears to be no more significant than a braided river channel cutting into its own overbank deposits.

Regional Fault Patterns

The large scale faults interpreted from seismic, landsat and aerial photograph data are presented in Enclosure 3.

Several major faults are recorded on the 1:100 000 geological sheets of the area and these were inspected in the field at many locations. Many minor faults in the basin are splays off the major trends. In the case of the east-northeasterly trend parallel to the basin margins, seismic evidence has demonstrated that repeated parallel fault systems are present across the basin.

Figure 3-2 from Sweet and Slater (1975) shows the pattern along the northern basin margin. Sweet and Slater identified the east-northeasterly fault trends comprising the Tin Hole Hinge Line on the northern edge of the Murphy Inlier, and the Fish River Fault Zone on the southern side of the Murphy Inlier as belonging to the earliest phase of deformation. The Fish River Fault Zone is down thrown to the south by several hundred metres. Although some movements may have occurred during sedimentation in the McArthur and Mount Isa Basins, the main east-northeast trending fold axes and faulting took place later. However, the lack of major displacements in the South Nicholson Group north of the Elizabeth Creek Thrust, suggested that the main movements took place before this group was deposited; therefore most of the deformation was probably late Palaeoproterozoic, synchronous with the basin deposition. From the detailed seismic data it became clear that this interpretation was rather simplistic as early normal growth faults complicated the picture. Additionally, the South Nicholson Group is compressively deformed south of the Elizabeth Creek Thrust.

The Calvert Fault is the most prominent of the northwesterly trending faults. It exhibits a left lateral displacement of 1000 m in the Carolina Sandstone Member of the Siegal Volcanics in the McArthur Basin. This can be explained by a vertical movement of 100 m down thrown to the southwest (Sweet and Slater, 1975; Figure 3-2). Interestingly the major Calvert Fault that is prominent in basement appears to change direction within the basin and splay. At a regional scale this northwest-southeast trending fault parallels several other major faults in the region, particularly the Termite Range Fault and the Bulman Fault in the McArthur Basin and so may relate to regional stress patterns that can be interpreted as compression from the south and east.

The northwesterly trending faults, particularly the Calvert Fault, have a much greater effect on the basement rocks than on the cover, and it seems that there were several periods of movement along them, including some movements that took place after the intrusion of the Nicholson Granite Complex, but before the deposition of the Westmoreland Conglomerate. The Westmoreland Conglomerate shows some evidence of syndepositional movement (Sweet and Slater, 1975). Although the movements along these faults were later than movements along the east-northeast trending faults, they were probably both active at several times in the Palaeo- to Mesoproterozoic. The Calvert Fault appears to have produced virtually no displacement of the South Nicholson Group, the youngest Proterozoic group in the region.

Seismic data confirmed the outcrop observations that the east-northeasterly fault trend is the most prominent within the basin. These faults are old with syndepositional movement only occurring within the earliest part of the basin sequence. It appears this trend formed early as down to the north normal rift style faults or half grabens. These were later reversed by thrusting in some areas to form the major potential petroleum entrapment structures observed today.

Detailed aerial photograph interpretations

The results of the aerial photograph work comprised a map illustrating both the surface structure and geology in the outcrop area of ATP 423P (Australian Photogeological Consultants, 1990) and specifically near Connolly Valley as described above (Figure 3-1 and Enclosure 4). This interpretation provided a valuable guide to the fault pattern of the region and were used to site the Connolly Valley seismic grid over two large surface anticlines in the basal Constance Sandstone Formation.

The fast track exercise of proving a drill target at Connolly Valley using aerial photograph interpretation was not successful (Section 3.8.1, Seismic analysis, Structure).

Stratigraphic and geological information

Useful stratigraphic and geological information was obtained from both the Landsat and aerial photograph data sets. Primarily this related to outcrop inspection and unit correlation and is reported where necessary in Section 3.7, Lithostratigraphy.

3.2.2 Magnetic data

AGSO magnetic data is available covering the entire Mount Isa Basin at a nominal 2 km line spacing. This was studied as enhanced images covering both the basin at a regional scale and in detail over the northern basin. A composite trend contour map derived from reduced 1:250 000 scale data sets was used in the initial phase (Enclosure 5), but the enhanced image processed data was found markedly superior. The magnetic map of Australia was of considerable assistance in deciding the regional trends that have affected the Mount Isa Basin.

The magnetic map of Australia

The magnetic map of Australia provides a full coverage of the Mount Isa Basin and clearly highlights the structural trends that have significantly altered the regional magnetic character over the area of the basin. This map (along with the regional gravity) shows a major break between the Mount Isa Basin and the

Willyama Block to the south. The north-south aligned structures in the northern Mount Isa Basin can clearly be observed to extend south and north of the exposed basin.

Regional magnetic coverage

Magnetic susceptibilities measured from outcrop samples in the northern Mount Isa Basin enabled a better qualitative interpretation of the various aeromagnetic data sets (Table 3-1, over page).

Regional aeromagnetic images such as the ones presented in Enclosure 1 clearly show the depositional margin of the northern Mount Isa Basin. Magnetic activity within most of the basin is quiet while the basement rocks and parts of the volcanic sequence immediately overlying, show intense dipoles when exposed as outcrop or under shallow Mesozoic cover. This magnetic contrast together with the regularly spaced seismic grid enabled the northern basin margin to be mapped with confidence.

ROCK SAMPLE LOCATIONS	MAGNETIC SUSCEPTIBILITY MEASUREMENTS (SI UNITS)
South Nicholson Group	
Mullera Formation	
DDA 130	$0 - 40 \times 10^{-5}$
Constance Sandstone	
Outcrop sample (Connolly Valley)	Not detectable at 10^{-5} level
Fickling Group	
Doomadgee Formation (upper McNamara Group)	
Outcrop sample (Wire Creek)	$0 - 5 \times 10^{-5}$
Walford Dolomite (lower McNamara Group)	
Outcrop sample (Wire Creek)	$0 - 20 \times 10^{-5}$
Peters Creek Volcanics	
Outcrop sample (Wire Creek) Ptp_5	$30 - 50 \times 10^{-5}$
Outcrop sample (Wire Creek) Ptp_5	$5 - 15 \times 10^{-5}$
Murphy Inlier	
Amoco GRQ 81-2	**$5 - 100 \times 10^{-4}$**

Table 3-1. Magnetic susceptibilities of outcrop and drill core samples from the northern Mount Isa Basin

Enhanced magnetic images

Using a range of processing techniques to further enhance the magnetic contrasts within the sequences many images were produced (Enclosure 1). These images refined the basin character by highlighting many fault trends and separating the Budawadda Basalt Member as a particularly strong continuous magnetic marker horizon (compared to the complexity of magnetic data from near Mount Isa (Leaman, 1991b). Of interest is the completely non-magnetic character of the Train Range Ironstone which crops out south of Elizabeth

Creek. This character is believed to derive from the chamositic oolitic composition of the unit. The Train Range Ironstone is discussed in detail in Sections 3.7.4 and , Chapter 6.

3.2.3 Gravity data

Gravity data based primarily on the AGSO 12 km grid provides full coverage of the Mount Isa Basin at a low resolution.

The gravity map of Australia

The gravity map of Australia highlights many characteristics of the Mount Isa Basin. Most significant are the pronounced north-south linear trends in the southern Mount Isa Basin near Mount Isa itself. At this location the Kalkadoon-Leichhardt Block is a major gravity high suggesting thin low density granitic intrusions and sedimentary section underlain by high grade metamorphic basement (Dr. M.D. Muir pers. comm., 1991). This folded and faulted trend can clearly be traced south to the Cooper and Warburton Basins. South of these younger basins the trend is again clearly visible in the rocks of the Willyama Block. This characteristic is further discussed in Section 3.4, The Mount Isa Basin.

Wellman (1992) described the structure of the Mount Isa region implied from gravity and magnetic anomalies. His analysis showed that many basin details are masked by the lack of contrast with the basement rocks and by post-depositional structural deformation. McIntyre and Wyatt (1978) were also able to map the regional geology of the Willyama Block and its surrounds using gravity and magnetic data, but did not observe any basement contrast. These situations appear different to the level of contrast between the McArthur Basin and its basement where Plumb and Wellman (1987) were able to map several deep troughs.

Enhanced Bouguer gravity images

Bouguer gravity data from the northern margin of the Mount Isa Basin responds to the east-west structuring in the basin and suggest deepening to the south where the thickest basin sequence is observed from the seismic data. Two significant depocentres appear to be present under the Georgina Basin where a thickening of the Mount Isa Basin can be inferred. The relatively coarse grid size of the gravity data compared to the magnetic data means that even basin margin interpretations based solely on the gravity are somewhat ambivalent. For example, the east-west structural trends near the Mount Isa Basin northern margin, which are so clear in the magnetic data and confirmed by the seismic information are very difficult to recognise from the gravity images.

At a regional scale, the area west of Mount Isa is a gravity high, possibility related to basement uplift south of the foreland sequence contained in the northern Mount Isa Basin. This interpretation is similar to the findings of

Kruger and Keller (1986) in the Ouachita Mountains area south of the Arkoma Basin.

3.2.4 Local gravity and magnetic data acquisition

Local gravity and magnetic data can be used to model geology. Seismic data was initially acquired in 1990 over Connolly Valley (seismic section 90BN-13, composite section, Enclosure 6). When repeated processing failed to adequately image a confirmed surface four-way closure the existing regional magnetics, Landsat and aerial photography data were augmented with ground magnetics and gravity to develop a structural model indirectly.

Before implementing the ground gravity and magnetic field work, theoretical gravity and magnetic models were generated for the Connolly Valley area (Barlow, 1991). The strike of the target was assumed to reflect the Landsat and surface feature while the dimensions were based on the similar but seismically well defined structure Egilabria-1. Model parameters are set out in Table 3-2 with the resulting calculated profiles illustrated in Figure 3-3 for the gravity and magnetics.

A density contrast exits between the Walford Dolomite of the lower Fickling Group and the clastic formations of the upper Fickling and South Nicholson Groups above (Mullera Formation, Constance Sandstone, Doomadgee Formation and Mount Les Siltstone) and the Peters Creek Volcanics below.

Both the sandstone and the volcanic formations are silicified and should have densities of about 2.7 gcm^{-3} while the dolostone is assumed to have a density of between 2.8 and 2.9 gcm^{-3}. The resulting density contrast of up to 0.2 gcm^{-3} would enable a target of Egilabria proportions to be easily identified at 1000 m depth. Density measurements on samples from these sequences by CRAE (Mr J.V. Main, pers. comm., 1990) supported these estimates although Main considered 0.2 gcm^{-3} was near the upper contrast limit.

The magnetic model (Figure 3-3) was based on a similar target shape and assumed a susceptibility contrast of 0.0025 cgs. This figure was derived from measurements on core and outcrop samples (Table 3-1). The contrast is greatest between the magnetic basement and Peters Creek Volcanics compared to the essentially non-magnetic sedimentary rocks above. Depth to the top and thickness of the volcanic sequence at Connolly Valley were unknown.

From the model (Figure 3-3) it can be seen that the anomaly amplitude was relatively small and may be masked by noise or by greater depth of burial (i.e. the depth to target is deeper than predicted).

Clearly the success of using potential field data to define the Connolly Valley structure depended on the gravity work. The gravity field generates an anomaly that better reflects the physical structure and, in this case, is less open to interpretation ambiguity. However, given the ease of magnetic data collection, the uncertainty in model parameters and the limited number of susceptibility measurements, magnetic traverses along lines were undertaken together with the gravity work.

PARAMETER	GRAVITY	MAGNETICS
Contrast	0.2 gcm^{-3}	20 x 10^{-5} SI ≡ 0.0025 cgs
Contrast Source	Walford Dolomite	Peters Creek Volcanics
Strike	060° NE	060° NE
Profile	150° SE	150° SE
Plunge	0°	0°
Depth to Top	300 m	1 000 m
Thickness	700 m	400 m
Width at top Width at bottom	2 000 m 1 000 m	1 000 m 1 000 m
Model	2D polygonal cross-section with ∞ strike	2D polygonal cross-section with ∞ strike
Maximum anomaly	1 mgal	10 Nt
Instrument Capabilities	0.05 mgal	0.5 Nt

Table 3-2. Gravity and magnetic model parameters (from Barlow, 1991)

The conclusions adapted from Barlow (1991) were:

1. The gravity data at close station intervals over Connolly Valley did not identify roll over of the sedimentary section. It is not clear however, whether there is insufficient density contrast in the Walford Dolomite to generate a gravity anomaly at the expected depth.

2. The field gravity work was more useful than the magnetics and showed structures at depth concomitant with the geomorphological feature over Connolly Valley. However, the structuring observed is considerably more complex than anticipated and the depth and size of the anomaly would not appear to relate to folding of the Walford Dolomite. The dolostone, with an assumed density of 2.9 gcm^{-3} provided the only known density contrast against silicified rocks of the northern Mount Isa Basin.

3. The magnetics were of little benefit in identifying closures in the northwestern portion of ATP 423P. The long wavelength, low frequency nature of magnetic features observed, make ground traverses redundant. The aeromagnetic data however, are useful in defining regional structuring of the basin and has delimited a large fault structure that controlled early basin sedimentation in the Connolly Valley area. Based on proprietary Western Mining airborne magnetic data over Connolly Valley, clearly the long wavelength nature of the magnetic response in the region makes ground work unnecessary.

4. Both ground and airborne magnetic data acquired over Connolly Valley showed a major fault structure that controlled early basin deposition near the northern margin of the basin. A susceptibility contrast of 0.002 cgs was used to model the Peters Creek Volcanics overlain and underlain by essentially non-magnetic rocks. As with the gravity data, the magnetic anomaly is not symptomatic of sedimentary folding and a deeper, more regional, structural

element is inferred as the source of the anomaly. (The basin structure referred to above is the lateral strike equivalent of the fault between seismic sections 91BN-19 and 91BN-30 under the Nicholson River).

3.2.5 Radiometric data

Contoured airborne radiometric data from the northern Mount Isa Basin were examined to see if any useful regional variations were present. Although the various lithological units within the basin contain different amounts and types of radioactive minerals, the unavailability of image processed data meant that little use could be made of radiometrics in the type of regional basin analysis being conducted for this thesis.

Some radioactive anomalies observed over the Murphy Inlier appeared to relate to known uranium deposits (Section 6.4.4, Uranium).

3.3 DRILLHOLE DATA

Many drillholes have been sunk throughout the Mount Isa Basin, but most work has concentrated on local mineral anomalies in the southern Mount Isa Basin. Although the importance of regional stratigraphic controls has been recognised, the high degree of basin deformation has meant that ideas of basin hydrodynamics such as are relevant in the oil and gas industry or MVT exploration in the Appalachian Basin have not been applied. For these reasons much of the data are difficult to interpret in terms of detailed lithofacies and lithostratigraphic maps. The major exception to this is the 1:100 000 scale AGSO geological maps of the region.

Along the northern margin of the Mount Isa Basin where oil and gas exploration potential exists, several mineral and petroleum exploration programs have been undertaken and these provided an excellent lithostratigraphic framework. Before the Comalco work, Amoco drilled five fully cored stratigraphic wells during 1983 and the DME (GSQ) drilled two holes in the southern portion of the northern Mount Isa Basin. The details of the different programs are presented in Section 3.7, Lithostratigraphy, where the various stratigraphic units are discussed. Figure 3-4 illustrates the locations of the various drillholes that were relogged and used to construct the regional lithostratigraphic control in the northern Mount Isa Basin.

During petroleum exploration within the northern Mount Isa Basin, as shown in the frontispiece, the wells drilled were Beamesbrook-1 in 1988 plus Desert Creek-1, Argyle Creek-1 and Egilabria-1 in 1992. These wells covered the full foreland and most of the drift phase stratigraphy in the Bowthorn Block. Of particular importance was that while testing the basin for hydrocarbons, the wells also tested and confirmed the drift-foreland portion of the basin model.

3.4 The Mount Isa Basin and the northern Mount Isa Basin

Geology's three key axioms describe basin development. These are:

1. The principal of uniformitarianism.
2. The law of superposition.
3. The idea that sediment is transported down slope and accumulates in sedimentary basins.

The use of these ideas alone is often necessary especially where there is a lack of age constraint data that can be determined from Palaeo- and Mesoproterozoic sequences. In the case of the Mount Isa Basin, application of these fundamental principles is essential because of deformation, lack of basin exposure, lack of age constraint data and the prior difficulty in recognising the basin itself.

The Mount Isa Basin is a new idea, or paradigm, (McConachie et al., 1993) to describe the area of Palaeo- to Mesoproterozoic rocks south of the Murphy Inlier and inappropriately described as the Mount Isa Inlier (see section 1.10, The Mount Isa Inlier). The new basin idea presented in this thesis allows the characterisation of basin-wide structural deformation and the recognition of areas with petroleum exploration potential.

The application of seismic exploration within ATP 423P at the northern margin of the basin was critical to the recognition and definition of the Mount Isa

Basin. The northern Mount Isa Basin is structurally analogous to several Phanerozoic basins, but as with all basins it contains unique characteristics, a function of its individual development history.

The northern Mount Isa Basin upon which this thesis concentrates, is the basin area northwest of the Mount Gordon Fault (Figure 3-5). The remainder of the basin south and southeast of the Mount Gordon Fault, is referred to as the southern Mount Isa Basin. Isolated remnants of lithostratigraphically equivalent rocks may occur near MWE Burketown-1 in isolated small half-grabens (Perryman, 1964). It should be noted that based on 373P seismic data, these half grabens are not in any way similar to the probably fictional "Burketown Depression" of Smart et al. (1980), the existence and delineation of which was based solely on gravity interpretation.

3.4.1 Concept

The concept of the Mount Isa Basin requires a change of scale compared with the many previous interpretations spread through the literature. The sedimentary nature of the sequences has never been in serious dispute (unlike the situation at Broken Hill). This harks back to the early idea of the Mount Isa Geosyncline that in modern terms, is quite close to the current interpretation. Much debate has raged over the relationship between the Eastern Succession (Fold Belt) and the Western Succession (Fold Belt). By comparison, little attention has been paid to the northern Mount Isa Basin (former Lawn Hill

Platform and South Nicholson Basin) that is the principal topic of analysis and discussion in this thesis.

The use of seismic stratigraphy along the northern basin margin enabled the recognition and testing by drilling of gently deformed sequences within the original basin, in an area where there has been little post-depositional faulting. The targeted seismic stratigraphic sequences comprised basal syn-rift volcaniclastic rocks, passive margin carbonate and foreland clastic rocks that describe the syndepositional tectonic evolution of the basin.

A greater question, yet to be fully investigated, concerns the undoubted existence of the Palaeo- to Mesoproterozoic Carpentarian Superbasin that is analogous to the Centralian Superbasin of Walter et al. (1992).

3.4.2 Character - Boundaries and shape

The eastern, southern and western boundaries of the Mount Isa Basin are obscured by the younger Carpentaria, Eromanga and Georgina Basins (Figure 2-4). The northern depositional margin of the basin is the metamorphic, intrusive and volcanic complex called the Murphy Inlier. These older rocks and their equivalents further south comprise the seismic basement to the Mount Isa Basin sequence. Basement further south nearer the orogenic belt is less easily identified due to the extensive regional metamorphism that has reduced the basin-basement contrast.

Basement units are thought to include the Murphy Metamorphics, Cliffdale Volcanics, Yaringa Metamorphics, Mary Downs Gneiss, Sulieman Gneiss, St Ronans Metamorphics, Leichhardt Volcanics, Kurbayia Migmatite, Plumb Mountain Gneiss, and Double Crossing Metamorphics. The intrusions that pre-date the development of the Mount Isa Basin are believed to comprise the Nicholson Granite, Yeldham Granite, Big Toby Microgranite, Ewen Batholith and the Kalkadoon Batholith.

3.4.3 Components

Structural elements

The Mount Isa Basin consists of three distinctly structured areas. From the south to the north they are (new names) the Cloncurry Orogen, the Riversleigh Fold Zone and the Bowthorn Block.

The Cloncurry Orogen comprises the area and sequences equivalent to the Mount Isa Orogen of Plumb et al. (1980) with the name change to distinguish this area from the more widely applied concept of the Mount Isa Basin. It is divided into three structural blocks (see Figures 3-5 and 3-6) in a fashion similar to Blake (1987). These are, from west to east, the Leichhardt River Block, the Kalkadoon-Leichhardt Block and the Mary Kathleen Block. The precise relationship of the Willyama Block at Broken Hill to the structural blocks in the

Cloncurry Orogen is unknown at this stage (see Section 3.4.4, The Carpentarian Superbasin).

The Riversleigh Fold Zone is a folded and faulted region south of the Bowthorn Block. The Riversleigh Fold Zone includes much of the area formerly called the Lawn Hill Platform (Plumb and Derrick, 1975). Several fold anticlines exhibit deeply eroded cores resulting in good geological exposure throughout the Riversleigh Fold Zone.

The Bowthorn Block, which is located between the Elizabeth Creek Thrust Zone and the Murphy Inlier consists of an asymmetric wedge of volcanic, carbonate and clastic rocks (see diagrammatic cross-section, Figure 3-7 and line of section location, Figure 3-8. This section follows the significant trend direction first recognised by Day et al. (1983). The Bowthorn Block comprises the area over which seismic acquisition was undertaken as part of the ATP 423P exploration. It ranges from over 10 000 m stratigraphic thickness near the Elizabeth Creek Thrust in the south to less than 2000 m immediately south of the Murphy Inlier in the north. The Bowthorn Block is relatively undeformed, but it does contain a series of reverse faults trending east-west that are interpreted from seismic data to be down-to-the-north normal faults that have been reactivated in some areas as thrusts in a manner similar to that described by Wuellner (1986) for the Marathon and Val Verde Basins of west Texas.

The major change in structural style within the basin occurs between the northern Mount Isa Basin (Bowthorn Block and Riversleigh Fold Zone) and the southern Mount Isa Basin (Cloncurry Orogen). These areas are separated by a major dextral strike slip fault (the Mount Gordon Fault) with a lateral displacement of up to 10 km. Geological correlations across the fault (based on 1:100 000 scale mapping) appear convincing. In keeping with this structural variation throughout the basin, thrust fronts can be classified using the system of Morley (1986), as "buried" in the Bowthorn Block and northern Riversleigh Fold Zone and distinctly "emergent" throughout the southern part of the basin. Using the criteria developed by Harding (1990) it is inferred that wrench faulting associated with the thrusting may have been significant for some fault systems in some areas.

Fault timing based on interpretation of the Bowthorn block data appears relatively straight forward. Early thick-skin, basement-involved, down-to-north normal faults comprised the earliest faults. Thin-skin tectonics with sled runner thrusts and thrust reactivation of the earlier normal faults made up the second generation of movement. Late stage basement-involved wrench faults and gentle east-west warping can also be interpreted from the seismic grids in the Bowthorn Block.

It is noted that aerial photograph interpretation of faults was less successful in deciding either timing or directions of movement. Gentle reactivation appears to distort greatly the interpretations obtained from surface observations.

Stratigraphic breakdown

As palaeontological control is not available in such old rocks, the palaeochronostratigraphic variation in the Mount Isa Basin is difficult to assess. The various geochemical dating techniques exhibit error bars that are too great to enable reliable rock age comparisons to be made within a basin deposition period. The major seismic sequence stratigraphic changes in the basin occur over longer periods and larger areas and may therefore be distinguishable by geochemical dating in the future.

Lithostratigraphically, the Riversleigh Fold Zone and the Bowthorn Block consist of basal volcanic and volcaniclastic rocks plus the overlying McNamara, Fickling and South Nicholson Groups. Extensively deformed, equivalent and possibly older, formations are contained within the Cloncurry Orogen or southern Mount Isa Basin (Figure 3-6). Although many formations must be equivalent, structural complexities and the limited data require the continuing use of the current nomenclature. The great structural complexity due to fault overprinting of the rift volcaniclastic rocks and other sequences in the Cloncurry Orogen (Leaman, 1991a; Lister, 1986) means that lithostratigraphic correlations in that area are very difficult to make.

The South Nicholson Group probably along with the Pilpah Sandstone and Quamby Conglomerate, comprise a later phase of now largely eroded fluvial and shallow marine deposits within the Mount Isa Basin. (The Knapdale

Quartzite of the Mount Albert Group may also be an equivalent unit). The suggested relationship is shown on Figure 3-6. The name South Nicholson Basin is now outmoded as this terminology only applied to the South Nicholson Group unlike the original broader definition in Brown et al. (1968) who applied the name to the full stratigraphic sequence.

3.4.4 The Carpentarian Superbasin - Contemporaneous, associated and contiguous basins

Many other areas of contemporaneous Proterozoic deposition are recognised throughout Australia and elsewhere (Tennant Creek Block, Georgetown Block, Arunta Block, Gawler Block, Wilkes Land in Antarctica, etc.), but their precise relationship to the Mount Isa Basin has not yet been determined. This superbasin concept is analogous to the Neoproterozoic system described by Walter et al. (1992).

McArthur Basin

From the lithostratigraphy reported by Powell et al. (1987), Jackson et al. (1987), Sweet and Hutton (1980) and Sweet and Slater (1975) along with the seismic data and lithology analyses from ATP 423P, it has been possible to recognise a high degree of correlation between the northern Mount Isa Basin and the southern McArthur Basin. The basic aspects of this correlation are presented in Figure 3-9 which contains a simplified representation of the northern Mount Isa Basin data. The discussion that follows was derived from a meeting with Drs M.D. Muir, K.D. Tuckwell, D. Taylor and Messrs J.V. Main, K. Lanigan of CRA and P.W. Stainton, J.N. Dunster, A.D. Schaap, M.G. Barlow and the author, all with Comalco Aluminium Limited.

Basin Architecture and Burial History

The McArthur Basin was considered to be a rift basin overlain by a sag phase represented by the deposition of the Roper Group. This rift-sag idea was similar to previous interpretations of the Mount Isa Basin sequence (e.g. Jackson et al., 1990). Three prominent features within the basin are the Batten Trough, the Urapunga Ridge (probable Inlier - parallel to the Murphy Inlier) and the Beetaloo Sub-basin. The Roper Group, which is the final phase of deposition within the basin, exhibits the broad geometry of a cratonic downwarp with formations and members readily correlated over vast areas. The Batten Trough is actually several half grabens dipping to the west and this is particularly evident on the southern side of the Urapunga Ridge.

Large (1992) described the north-south faults in the McArthur Basin as superficial and not indicative of the underlying structure, but Dr M.D. Muir pers. comm. (1993) has measured a 10 km vertical throw on the Emu Fault. This is very similar to the situation in the southern Mount Isa Basin, where later north-south overprinting of earlier east-west faults appears to be a common feature.

Potential Field Data (Landsat, Magnetics, Gravity)

By contrast with the northern Mount Isa Basin, the McArthur Basin is well defined by the gravity trends in the area. Although magnetics is of little use, gravity lows do correspond to thicker sequences and intrusive syenitic rocks.

Chrono-biostratigraphy

The various age dates from the region that have been determined from uranium-lead, rubidium-strontium and potassium-argon work are illustrated in Plumb (1990), reproduced here in Figure 3-10. The results show the sequence, from the base of the Tawallah Group and Peters Creek Volcanics through to the top of the Roper and South Nicholson Groups, to range between 1700 to 1400 Ma, in the Palaeo- to Mesoproterozoic.

Seismic Data

Seismic data in the McArthur Basin is much more variable in quality due primarily to karstic development in overlying Phanerozoic limestones. The packages mapped show gradual thickening away from the Urapunga Ridge, but this is thought to occur only on a regional scale typical of an intracratonic sag sequence (or the late molasse phase in the cratonic part of a waning foreland basin). Locally the seismic packages exhibit constant thickness, and good regional correlation is possible. Prominent reflectors within the basin are dykes, sills and carbonaceous units.

Well Logs and Lithostratigraphy

Oil exploration stratigraphic work in the McArthur Basin has mainly concentrated on the Roper Group, which comprises the uppermost part of the McArthur Basin sequence. This is thought to be equivalent to the upper McNamara and upper Fickling Groups plus the South Nicholson Group in the northern Mount Isa Basin. This assumption is based upon correlation of lithotypes such as the Sherwin Ironstone with the Train Range Ironstone in the South Nicholson Group and the general character and thicknesses of the sequences. The Roper Group however appears much less deformed than the equivalent rocks in the northern Riversleigh Fold Zone of the Mount Isa Basin. This is probably a function of the more intracratonic setting of the McArthur Basin.

Pacific Oil and Gas drilled more than 20 holes in the Roper Group and good lithostratigraphic correlations between wells have been achieved. An unconformity has been recognised at the base of the Bukalorkmi Sandstone Member in the upper part of the group and others may be present in the sequence. The Constance Sandstone is thought to be equivalent to the Bessie Creek Sandstone. The Velkerri Formation, which is a dark carbonaceous mudstone very rich in organic matter may be equivalent to the Mullera

Formation of the South Nicholson Group. The Velkerri Formation contains tuff markers at the base of the middle portion. Although not yet recognised in the Mullera Formation, if present they may establish a firm correlation.

Dolerite sills are also common in the middle Velkerri and these are widely observed on seismic sections. The dolerites grade to diorite and gabbro in the centre of the sills, with crystal sizes ranging up to 1 cm. The dolerites are present as both sills and dykes and occur lower in the stratigraphy to the east possibly indicating regional basin tilt. In ATP 423P, mineral drillhole Amoco GRQ 81-2 (Figure 3-4) penetrated basement below the Carpentaria and Mount Isa Basins and immediately north of the Mount Isa Basin subcrop. This basement unit was found gabbroic in composition and probably part of an old intrusion. Dyke-like features, possibly intruding fault planes within the Murphy Inlier, are present on seismic sections. Thin sections of these basement rocks were reported by Moultrie (1991c).

Throughout the McArthur Basin, highs on gamma ray logs correlate with high TOC levels, and in places, with tuffaceous members. Similar tuffaceous members are known to occur at Century and Mount Isa.

Provenance for the Roper Group was demonstrably different to the Nathan and the McArthur Groups, which were both internally sourced. This is comparable to the South Nicholson, upper Fickling and upper McNamara Groups. Locally incorporated internally sourced material (stromatolitic clasts) were observed at Wire Creek near the base of the Constance Sandstone.

Structural Styles

The McArthur and Nathan Groups of the McArthur Basin are deformed near faults and at depth. The Roper Group exhibits little deformation except for small graben features such as those present near Jamison-1. The basin also contains anticlinal features of which the Broadmere Anticline is typical, along with sporadic fault-associated growth and drape features.

The Georgetown Block

Laing (1990) reported an "impressively close stratigraphic correlation" between the Soldiers Cap Group of the Mount Isa Basin, (plus the upper Willyama Group of the Willyama Block) and the Etheridge Group at Georgetown. The available data suggested an age of 1620 Ma for the Soldiers Cap Group (Beardsmore et al., 1988). The Etheridge Group in the Georgetown area is not well dated but lies between 1570 and 2200 Ma and this certainly overlaps with the ages reported for the Mount Isa Basin.

The Broken Hill Area (Willyama Block)

Several lines of independent evidence establish the link between the Mount Isa Basin and the Willyama Block at Broken Hill. Much of this data has been known for years but when incorporated into the rift-drift-peripheral foreland basin model in a plate tectonic context, a convincing picture emerges. The common features of the two areas are:

1. Both areas contain metamorphosed lithostratigraphically similar sedimentary sequences, and several authors have argued for a sedimentary origin for mineralisation at Broken Hill. King (1975), in referring to "Stanton's metamorphic camouflage" at Broken Hill, strongly alluded to his preferred model of a sedimentary origin for the deposit. Johnson and Klingner (1975) argued strongly for a syngenetic origin for the Broken Hill ore deposit. Willis et al. (1983), Wright et al. (1987) and Stevens et al. (1988) all proposed detailed sedimentary models for the deposit. Saxby (1981) considered McArthur River, Mount Isa and Broken Hill were mineral deposits at three different stages of metamorphic development of somewhat similar metalliferous sediments.

2. Based upon the available isotopic rock dating (Stevens, 1986; Page, 1981; Wyborn et al., 1988), the rocks of each area are about the same age.

3. Both areas contain large deposits of lead-zinc and other minerals that are, by virtue of their size and mineralisation style, uncommon on a world scale.

Taylor (1971) has suggested that the Broken Hill deposit could have contained much more carbonaceous matter than now, making it quite similar to the Mount Isa area. Carbon is present as graphite but rare today at Broken Hill because of reaction with water to form methane and carbon dioxide during metamorphism. Based on carbon isotope data Hamilton (1965) concluded that the graphitic carbon in the Broken Hill lode is most probably biogenic in origin.

4. The original sedimentary (basin) sequences in each area have been metamorphosed with a clear thermal trend from north to south (Figure 3-11) very similar to the trends observed in the southern Appalachians (Jamieson and Beaumont, 1988). A similar trend was reported in Hamilton and Muir (1974) for McArthur River, Mount Isa and Broken Hill. The northern most part of the Mount Isa Basin is immature today for oil generation, while the southern Mount Isa Basin is metamorphosed to upper greenschist and upper amphibolite facies. By contrast, the Willyama Block has reached hornblende granulite grade. Stevens (1986) attributed this metamorphism to up to 20 km of burial in the southern Broken Hill area. Barnes (1988) showed significant variation in metamorphic grade within the Broken Hill Block ranging from andalusite+muscovite in the north to two pyroxenes with retrograde kyanite and staurolite in the south.

Deformation increases markedly from north to south through the Bowthorn Block, Riversleigh Fold Zone, Cloncurry Orogen (see cross-section and line of section location map Figures 3-7 and 3-8) and Willyama Block. Crystal grainsize of the lead-zinc ores also increases north to south in response to the change in regional metamorphic conditions. Increasing temperature and pressure trends are important characteristics of regional metamorphism in asymmetrically loaded basins as shown in Figure 3-12.

5. The Mount Isa and Broken Hill areas are separated by the Warburton and Cooper-Pedirka "failed rift style" basins which formed during the Cambro-Ordovician and Permo-Triassic periods respectively. These appear to have simply divided the old cratonised Proterozoic basin (Figure 3-13). The separation of the Willyama Block from the Mount Isa Basin is thought to have been a two stage process. The separation occurred along a north-west axis during the Cambro-Ordovician and a north-east axis throughout the Permo-Triassic. Mutter (1986) illustrated the character of continental rifting using seismic data and Nelson et al. (1992) described rift segment interactions and propagation in cratonic rifts.

The failed rifting event which probably occurred in the Cambro-Ordovician appears to be analogous to the breakup of Australia from Antarctica in the Late Cretaceous, even to the extent that continental wide activity may have occurred. Webby (1978) recognised the close association of activity in the Canning, Amadeus, and Warburton Basins during the latter part of that period. With this scale of events it is not too difficult to imagine the breakup of the original Proterozoic basin.

6. Enhanced regional magnetic and gravity images and the AGSO (formerly BMR) gravity map of Australia (Figure 3-14) show each of these areas to be of similar character (as noted by Stevens et al., 1988) with predominant north-south trends. Several matching disjuncts can be observed by closing these failed rifts (Figure 3-13).

7. The Cambrian limestones in the Burke River Structure of the southern Mount Isa Basin and the Bancannia Trough that separates the Euriowie Block and the Broken Hill Block within the Willyama Block, could easily have been continuous before breakup. Because the Cambrian of the Bancannia Trough appears to occur mainly as slices along the margin, it is possible that more extensive phanerozoic deformation has occurred near Broken Hill than at Mount Isa.

8. The Adelaide Geosyncline and the Toko syncline were possibly originally contiguous.

In addition, the lithostratigraphies at Mount Isa and Broken Hill are comparable. Wright et al. (1987) proposed a sedimentary model for Broken Hill. Laing (1990) noted a correlation between the upper Willyama Group and the Soldiers Cap Group of the Mount Isa Basin. Plimer (1992) reported meta-evaporites at the top of the Thackaringa Group and the base of the Broken Hill Group at Broken Hill. These may be similar to scapolites at Dugald River in the Mount Isa Basin and are possibly related to the meta-evaporites recognised by Cook and Ashley (1991) in the Olary Block of South Australia. Although manganese is common at Broken Hill, and is only present as scattered occurrences in the Mount Isa Basin, it is present in the McArthur Basin and may have been remobilised into the Cretaceous (?Tertiary) deposits at Groote Eylandt. The Cu deposit at Mount Isa does not appear to have any equivalent at Broken Hill, but lesser occurrences are present. If the Cu mineralisation formed later as concluded by King (1989) it may have been mobilised during metamorphic burial or at the time of the late stage east-west compressional deformational event in the Mount Isa Basin.

Other Areas (Tennant Creek Block, Arunta Block, Gawler Block, Musgrave Block, Wilkes Land Antarctica, etc.)

Several other areas of contemporaneous Proterozoic deposition are recognised throughout Australia, but their relationship to the Mount Isa Basin has not yet been determined. All are described in various publications the most significant being Blake et al. (1987) and Hughes (1990).

3.4.5 Overlying basins

Pre-Mesozoic basins overlying the Mount Isa Basin

Overlying the Mount Isa Basin are a range of geological units. The South Nicholson Group (Plate 4, b and d) which is reported later in this thesis is no longer afforded basin status.

Georgina Basin limestones and clastic rocks are present in the southwest. These are flat lying and unconformably overlie the McNamara Group with sporadic outliers at locations such as Century (Plate 4, a). The carbonates of the Georgina Limestone contain abundant phosphatic chert nodules in many areas (Plate 4, c) and are quite distinct from the rocks of the Mount Isa Basin.

No late Palaeozoic section has been identified near the Mount Isa Basin. The nearest is the Permo-Triassic of the northern Galilee.

Mesozoic rocks

Remnants of flat lying Mesozoic sedimentary rocks cap mesas sporadically throughout the area. In the Northern Territory these rocks are collectively termed the Mullaman beds (Petrel Formation) and are believed to be part of an extensive belt of Jurassic and Cretaceous sedimentary rocks that extended over much of the Northern Territory and Western Queensland. The sequence is probably continuous with the Gilbert River and Garraway Formations of the Carpentaria Basin and equivalent units in the Eromanga Basin that were deposited north and south of the Mount Isa Basin respectively.

Pre-Carpentaria Basin (Middle Triassic) deposition is known from the Boomarra area to the southeast (Williams and Gunther, 1989; McConachie et al., 1990a and b) and these rocks may extend to the Burketown area where anecdotal reports of "red rock" have been described from waterbores. The sequence is probably equivalent to the Galilee Basin that underlies much of the northern Eromanga Basin.

Outcrop examined during the field mapping in the northern Mount Isa Basin included variably ferruginous quartz sandstones in the region of the Connolly Valley seismic grid and red brown ferruginous sandstone overlain by white partly silicified siltstone and fine sandstone near the intersection of Wire Creek and the Nicholson River. Both these exposures contain Mesozoic trace fossils and moulds. Sweet and Slater (1975) reported plant remains from an outcrop between Wire Creek and Hedleys Creek near the Fish River Fault.

Most Mesozoic rocks in the area are readily identifiable on aerial photographs because of their physiographic expression and light colour. The units mapped as Mesozoic near Lead Hill are however not obvious on aerial photographs. Lead Hill itself is capped by a pebble to boulder conglomerate (Plate 14, a) and a similar outcrop occurs about one kilometre to the northeast. No Mesozoic fossils could be identified in the field at Lead Hill and the second outcrop was not examined on the ground. It must be acknowledged that the conglomerate could equally well be basal Doomadgee Formation or even South Nicholson Group. Palynological samples collected from Lead Hill were of little use because of extensive Cainozoic lateritisation resulting in oxidation of any palynomorphs present. Small areas of possible Mesozoic outcrop are therefore difficult to distinguish from Mount Isa Basin rocks, particularly where lateritisation and silicification have been intense.

Sweet et al. (1981) drew attention to the wide variation in the present elevation of the base of the Mullaman beds, and suggested that the beds were deposited on an uneven land surface probably in a series of north-south trending valleys. This seems more plausible than invoking post-Mesozoic fault movement to explain the bed's erratic distribution as the older rock sequences do not appear highly deformed. The Middle Triassic rocks east of the Boomarra Fault suggest possible Mesozoic movement on some major north-south faults in the Mount Isa Basin.

Cainozoic sediments and weathering profile

True Cainozoic sediments (they are certainly not all lithified to rock) were treated only superficially during this study. In strict terms they are assigned to the Karumba Basin of Doutch (1976). Areas of early to mid-Tertiary laterites, which are especially well developed on Doomadgee Formation siltstone (Plate

8, c) and Mesozoic rocks, were observed. Quaternary river conglomerates occur sporadically along both Wire Creek and Gorge Creek and are partially lithified in places. The sandy alluvial plains east of Wire Creek are believed to be older than the river conglomerates (Sweet et al., 1981).

Throughout the Lawn Hill area, a Miocene unit known as the Carl Creek Limestone is sporadically present in outcrop. The Carl Creek Limestone contains the Riversleigh fossil discoveries. Similar Miocene limestones occur in various places in the McArthur Basin.

3.4.6 Basin classification

Sedimentary basins like the Mount Isa Basin are difficult to classify. Many attempts at general basin classification have been made in the literature based on a wide range of criteria (Klein, 1991b, Figure 3-15). The intimate link between oil exploration and studies of large groups of the world's sedimentary basins has been a major stimulus to attempt to rationalise the various basin types.

Despite all of the classification attempts, sedimentary basins form in a continuum of varied settings with many individual characteristics unique to each basin. Subject to this constraint, broad plate tectonic and general lithospheric stress regimes can be utilised to categorise and simplify the many sedimentary basins of the world. This is particularly relevant when considered together with organic geochemical basin classification to assess the charge, migration, entrapment and retention characteristics of petroleum in sedimentary basins (Demaison and Huizinga, 1991) and the equivalent genetic classification system applicable to mineral exploration (Klein, 1991b).

Classification schemes

Basin classification schemes are primarily based upon plate tectonic concepts that provide a mechanism for basin formation, development and geographic setting. Multicyclic basins (sometimes called polyhistory basins, Kingston et al., 1983) are recognised where conditions change throughout the evolution of a basin. Classifications based upon petroleum industry criteria often utilise architectural characteristics that are directly related to plate tectonic settings. The modern basins observed throughout the world today are diverse and have formed due to stress response. The stress can be compressional, tensional, or rotational related to strike slip.

All of the basin types referred to in Table 3-3 can be related to several simple basin forming processes described by Allen and Allen (1991). The genetic mechanisms are as follows:

1. Basins due to lithospheric stretching.
2. Basins generated by flexure on continental and oceanic lithosphere.
3. Strike-slip or megashear-related basins.

All these processes appear to have had some impact on the Mount Isa Basin, although the deposition of the sedimentary sequences is interpreted to relate directly to the first two (Table 3-4). Several variations occur within each genetic type presented in Table 3-4.

Many stretching models have been proposed, principally McKenzie (1978) and Wernicke (1985) to account for the range of beta (β) factors, thermal histories and basin fills observed. For example, rifts with β greater than 2.0 usually contain basaltic volcanism, while those where stretching is less than 2.0 almost never have igneous rocks (Professor J.F. Dewey, pers comm., 1987).

Foreland basins and ocean trenches are examples of basins caused primarily by flexure of the lithosphere. Flexure of oceanic lithosphere near subduction zones can be responsible for the formation of deep ocean trenches. In intracratonic foreland basins, continental lithosphere is bent under the loads imposed by orogenesis.

Basins associated with strike-slip deformation are principally pull-apart rhombochasm style features related to deep seated strike-slip movement producing flower structures and Reidel shears at shallower depths. The precise geometry of these basins is controlled by the kinematics (convergent, divergent or parallel) of the fault system, the magnitude of the displacement, the material properties of the rocks and sedimentary infills in the deforming zone, and the form of pre-existing structures. Deposition in this kind of basin is usually simple to interpret from the tectonic setting and the basin architecture.

Basins genetically related to stretching or thinning of the lithosphere are rifts and sags on continental lithosphere and sequences (basins) formed at passive continental margins. These are all part of an evolutionary sequence Veevers (1981) called the "rift-drift" suite of sedimentary basins that relates most closely to the Mount Isa Basin data where multicyclic basin development appears to have occurred (Table 3-4).

Bally and Oldow (1984) distinguished three different families of sedimentary basins based on plate tectonic settings.
1. Basins located on rigid relatively undeformed lithosphere and not associated with the formation of megasutures.
2. Perisutural basins on rigid, relatively undeformed lithosphere, associated with, and flanking the compressional megasutures.
3. Episutural basins located upon and mostly contained within the megasuture.

Kingston et al. (1983) based their classification upon the following genetic criteria.
1. Type of lithospheric substrate.
2. Relative plate motion.
3. Location on the plate.
They deduced eight practical basin types that are continental interior sag, continental interior fracture, continental margin sag, continental wrench, trench associated, oceanic trench, oceanic wrench and oceanic sag.

Crowell (1984) examined basins along the general plan adopted by Kingston et al. (1983), but did so in the light of three genetic stages in basin history. These are usually three separate stages but at times and places they overlap.
1. Basin-forming tectonics.
2. Depositional sequences.
3. Basin modifying tectonics.

Klemme (1980) recognised eight types of basin within five major basin classes primarily based on architectural style. This scheme is based on features such as linearity, asymmetry and cross-sectional geometry, all of which are related to the basin tectonic setting and evolution. As with the classification of Huff (1980), Klemme's scheme is solidly oil industry based and designed specifically for gaining insights into frontier basins. The eight basin types recognised by Klemme were interior simple, composite complex, rift, downwarp, pull-apart, subduction, median and deltas (Compare this with Klemme, 1986; Figure 3-15). The eight classes used by Huff are divergent margin (including transform), deltas and fans, rifts and grabens, strike slip (including transform), back arc, fore arc, cratonic sag and foreland.

Kendall et al. (1985) described nine basin types modified from Klemme (1980) whose classification, they noted, illustrated the overlap and lack of clear distinction between various basin types, but did establish some general relationships. The Kendall et al. (1985) basin category types were simple cratonic, composite cratonic, rift, passive margin or pull-apart, subduction related borderland, retroarc foreland, peripheral foreland, interarc, pull-apart and wrench style.

Shannon and Naylor (1989) adopted a relatively simple classification scheme based upon the basin genesis and tectonic location. They defined seven basic basin types with a further polyhistory or composite category for basins with variable characteristics. Using a hierarchy of crust type, dominant plate movement, plate location and dominant structural movement giving a basin type: downwarp, rift, interior, foreland, subduction, pull-apart, delta and composite polyhistory basin categories were recognised.

Table 3-3. Various basin classification schemes

BASIN TYPES (sensu lato) AND FEATURES	LITHOSPHERE STRETCHING (FAILED RIFT)	LITHOSPHERE FLEXURE (FORELAND)	STRIKE SLIP (PULL-APART)	MOUNT ISA BASIN
PLATE SETTING	Intra-plate setting, can develop into a passive margin	Convergent, subduction related	Related to strike slip, small scale	Marginal plate setting in southeast, interior in northwest
TECTONIC DEFORMATION	Tensional, listric normal faults	Compressional, thrusts near orogen	Transpressional	Early tension, later compression
CROSS-SECTIONAL GEOMETRY	Symmetric, sometimes asymmetric	Asymmetric	Symmetric	Asymmetric
VOLCANIC BASIN FILL	Alkaline volcanic association, some tholeiites	Andesitic association, mostly island arc related volcanics, some tholeiites (most common in retroarc systems)	Variable	Continental tholeiites, basalts, rhyolites, intermediate volcanics, tuffs intercalated with clastics. Mostly at base of basin sequence
BASIN FILL SEQUENCE	Volcanics, clastics and evaporites in pre-rift, rift and sag phases	Coarsening upward mega-cycle of carbonate-flysch-molasse, minor volcanics	Variable, clastic dominated	Volcanics and volcaniclastics at base, overlain by carbonates, deep marine and shallow marine to fluvial deposits
HORIZONTAL BASIN FACIES	Coarse influx adjacent to margins	Coarse material near orogenic margin grading to finer distal facies	Coarse material near basin edge	Sandstone dominated near Mount Isa, siltstone and carbonate predominate in northwest
SUBSIDENCE RATE	Low to moderate (usually less than 0.1 mm/yr)	Moderate to very high (up to 100 mm/yr)	Moderate to very high	Low early, e.g. shallow water carbonates. High later, exceeded deposition rate producing deep water facies
BASIN DEPTH	Theoretical maximum 7.63 km at $\beta = \infty$ (McKenzie, 1978)	3 to 16 km	Usually less than 7 km	15 km based on maximum metamorphic grade (sequence stratigraphy in Blake, 1987 totals over 40 km is excessive and suggests fault repetition and facies changes)
BASIN EDGE	Fault controlled	Orogen bounded tapering to feather-edge	Wrench fault related	Feather-edge at Murphy Inlier, highly faulted near Mount Isa in the direction of the collisional zone
GEOTHERMAL GRADIENT (World average = 30°C/km)	High initially	Variable	High	High, 38°C/km (based on metamorphic grade at maximum burial)
UNCONFORMITY SURFACES	Subsidence related	Syntectonic unconformities at orogen grading to disconformities at feather-edge	Syntectonic, wrench related	Syntectonic on seismic data, early breakup related events present
BASIN DEFORMATION	Uniform, gravity slides near margins	Decreases away from orogen	Variable	Highly faulted and folded near Mount Isa, flat lying on Murphy Inlier

Note: Shading highlights aspects compatible with the known geology of the Mount Isa Basin

Table 3-4. Characteristics of the major basin types based on formational processes compared to the Mount Isa Basin

Based on Table 3-4 and the seismic data from ATP 423P, it is apparent that the characteristics of the Mount Isa Basin involve multicyclic character and that a stacked foreland sequence is recognisable, superimposed on and deforming the passive margin and rift phases.

Multicyclic and foreland basins

Foreland basins primarily result from the interaction of lithospheric plates. This type of basin can range in shape from elongate to arcuate with a range of basin styles and shapes existing along the length of plate interaction. Foreland basins are typically highly asymmetrical thinning away from the orogenic provenance region. This highly deformed area is the primary source of sediment. These basins are usually orogenic to post-orogenic in age with most of the basin fill derived from the rising mountain range. Foreland basins are commonly modified by late- or post-orogenic compressional structuring which is typically thin skinned and the initial foreland basin is commonly overlain by a successor molasse sequence.

Miall (1984) described four elements in the establishment of a foreland basin model, all of which appear to apply to the Mount Isa Basin. They are:

1. A basement of normal continental crust, the structural grain of which markedly affects isopach and facies patterns as a result of structural rejuvenation.

2. A dominantly marine to nonmarine clastic fill that may contain an upward coarsening transition from marine to nonmarine.

3. Sediments may be derived from an adjacent magmatic arc or growing fold-thrust belt, or from basement uplifts, or from a cratonic hinterland.

4. A structural style dominated by compressional folds and faults, with local intraformational unconformities attesting to syndepositional tectonism.

Two distinct genetic classes of foreland basin have been recognised (Dickinson, 1974; Kendall et al., 1985). Both classes are ensialic, overlying cratonic lithosphere. Both are associated with some degree of crustal shortening in tectonically active zones (Figure 3-16).

The first class is peripheral foreland basins situated against the outer arc of the orogen during continent-continent collisions. Basins developed in this setting include several formed adjacent to the Ouachita orogenic belt in the southern USA. The Timor Trench is a modern example. In this setting the Australian plate is being subsumed beneath the Sunda Arc. In peripheral foreland basins, sedimentation patterns are variable and both transverse and longitudinal palaeotransport directions occur. Other examples include the Middle East

Basin, Alberta Foreland Basin, Eastern Venezuela Basin, Papuan Basin, Appalachian Basin and the Arkoma Basin.

Retroarc foreland basins are the second class. These form on the landward side of magmatic arcs often linked to the subduction of oceanic crust. In this setting, basinal downwarp results from tectonic loading of back-arc thrust sheets. The continental lithosphere is flexed under the loads imposed by orogenesis. The competence of the lithosphere during low angle subduction may create overthrusting and retroarc basin development up to 1000 km inland of the continental margin (Lock, 1980). In both marginal and interior locations, proximal high energy alluvial fans grading to interior fluvio-deltaic systems prograde from the active orogenic flank toward the cratonic interior. Thick wedges of conglomerates, arkoses and lithic sandstones may be deposited depending upon the precise conditions. Thick coal seams may also develop. Thinner quartzose sandstones deposited in wave-dominated deltaic, barrier and shallow shelf environments are typical of the continental basin margin, but may also occur along the distal fringe of the major clastic wedge of the active margin. Deep marine sedimentation is rare but may occur where subsidence rates exceed deposition rates for sustained periods. The Bowen Basin is a retroarc foreland basin (e.g. McConachie, 1986b, 1992), and many basins associated with the Andean mountain chain in South America are typical examples of retroarc foreland basins.

Miall (1984) considered the term retroarc basin should be restricted to those foreland basins whose position can be clearly interpreted with respect to magmatic arc location and arc polarity. This involves differentiating the subducted from the overriding plate, and it is therefore necessary to construct the plate tectonic setting of the Mount Isa Basin (see Section 3.11, Plate tectonic setting)

Based on work described by Professor G.D. Klein (pers. comm., 1992) several features can be used to distinguish peripheral and retroarc foreland basins. The features observed in the Mount Isa basin are highlighted in the following Table 3-5. Based on the data in this table the Mount Isa Basin is interpreted to be a peripheral style foreland basin during the foreland phase of its development.

FEATURES	PERIPHERAL FORELAND BASIN	RETROARC FORELAND BASIN
FOLD AND THRUST BELT	Includes thrusted subduction complex	Composed of units correlative to underlying basement
VOLCANIC ACTIVITY	At a distance (few volcanic or volcaniclastic sediments)	Adjacent to basin (common volcanic and volcaniclastic sediments)
DURATION	Subsidence less than 10 Ma	Subsidence long term, greater than 10 Ma
LITHOSTRATIGRAPHY	Deep marine sediments shoaling upward to shelf, nearshore and non-marine sediments	Shelfal sediments shoaling upward to nearshore and non-marine sediments (deep-water sediments absent)
FLEXURAL SUBSIDENCE	Driven by thrust sheet loading and bending moment transmitted through the subducting plate	Driven by thrust sheet loading alone

Note: Shading indicates aspects present in the Mount Isa Basin

Table 3-5. Characteristics of peripheral and retroarc foreland basins compared to the Mount Isa Basin (from Klein, 1992)

Foreland basins are closely related to orogenic and thrust fold belts that often comprise cannibalised parts of the foreland basin (Denison, 1989; Burbank and Raynolds, 1988). This is the case for the Mount Isa Basin where disturbed rift, platform and foreland deposits are present throughout the Cloncurry Orogen. This feature could result in progressive younging from south to north of ore genesis within the greater Carpentarian Superbasin by progressive foreland advance following uplift and orogenesis.

The features observed in the two general forms of orogenic belts are presented in the Table 3-6 which highlights the aspects similar to the Mount Isa Basin. The data strongly suggests that the Mount Isa Basin is a compressional subduction related orogenic belt. An east-west strike with north-south compression is suggested as the syndepositional tectonic model for the basin.

Grotzinger and McCormic (1988) considered that foreland basins display three fundamental stages of evolution that can be observed in the lithostratigraphy of the Mount Isa Basin.

1. Initial, rapid submergence or drowning of an earlier, slowly subsiding platform (e.g. passive margin carbonates).

2. Deep marine flysch type sedimentation in a narrow axial trough; submarine fan and related deposits are common and show longitudinal sediment dispersal patterns.

CONVERGENT STRIKE-SLIP OROGENIC BELT	COMPRESSIONAL SUBDUCTION OROGENIC BELT
En echelon folds	Parallel to subparallel wavelike folds, no systemic en echelon folds
Great degree of basement involvement proximal to thrust belt	Lesser degree of basement involvement proximal to thrust belt
Mostly upthrusts	Mostly sled runner thrusts that peel off above basement, not basement involved
Narrow zone of deformed sedimentary cover lacking foreland detached structures	Wide zone of deformed sedimentary cover including foreland detached or foothills structures
Crustal shortening minimal	Crustal shortening can be extreme
No alpine ophiolites	Alpine ophiolites frequently associated, particularly if obduction occurs
Nil to little metamorphism	Metamorphism
No batholithic intrusions	Batholithic intrusions common
Volcanic belts not commonly associated	Volcanic belts frequent but not in peripheral foreland settings (At Mount Isa the Eastern Creek Volcanics are within the rift sequence)
Infrequent island arc association	Island arcs frequently associated but not in peripheral foreland settings
Deep water sediments (turbidites, flysch) or trench origin not common	Deep water sediments common
Melange rare	Melange common
Prior eugeosynclinal-miogeosynclinal association not common	Prior eugeosynclinal-miogeosynclinal association common
Lesser sediment thicknesses deformed	Great sediment thickness deformed
Deformation by gravity very minor	Deformation by gravity may be significant (This may be the case in the Cloncurry Orogen)
No particular early deformation	Earlier deformation may be normal faulting that affected pull apart
Molasse sedimentation modest	Molasse sedimentation may be extensive
Maximum length about 1000 km	Maximum length about 10 000 km
Generally straight	Straight or curved

Note: Shading indicates characteristics observed in the Mount Isa Basin

Table 3-6. Characteristics of convergent and strike-slip orogenic belts compared to the Mount Isa Basin (from Lowell, 1985)

3. Shallow marine to fluvial molasse type sedimentation associated with final filling of the basin, with sediment dispersal directed towards the foreland.

Variations on this general theme occur depending on plate rigidity, extent of convergence, erosion rates and corresponding rate of sediment supply. This format is very similar to the model described by Bally (1989, Figure 3-31).

Flexure is the key element in the generation of foreland basin stratigraphy. The large scale geometry comprises a thick wedge close to the deformed basin orogenic load, thinning to a feather edge next to the continental interior. This asymmetry is due to the relative rates of subsidence that are greatest at the site of the orogenic load and decrease in the direction of the peripheral bulge. This effect causes onlap of successively younger stratigraphic units onto the foreland. Basinward migration from the peripheral bulge results in offlap stratigraphic sequences. Flemings and Jordan (1990) produced a model to predict the stratal geometries and facies patterns produced during episodic thrusting in a nonmarine foreland basin. From the present study it is apparent that both the lithofacies sequence and the erosional unconformities provide the key to the stratigraphic record of thrust events in the northern Mount Isa Basin (see Section 3.8.3 Seismic stratigraphy).

Allen and Allen (1991) considered that the details of the deflection of the foreland plate depend on the following factors:

1. The flexural rigidity of the flexed lithosphere;
2. The nature of the distributed loads (topographic and thrust loads, horizontal end forces, bending moments, sediment and water loads);

3. Pre-existing heterogeneities.

It is therefore vital to consider the pre-existing condition of the lithosphere commonly described as the Wilson Cycle (Dewey and Burke, 1974). This cycle of rifting, drifting, subduction and collision implies that foreland basins should be superimposed on earlier formed passive margin and rift sequences. The lithosphere should therefore be rigid due to its previous heating and thinning with the first orogenic loads emplaced on oceanic bathymetries in the case of peripheral foreland basins. These features allow thick overthrust wedges to develop with little topographic expression. Passage of the flexural forebulge causes complex unconformities to develop, and the progressive overthrusting of the plate causes migration of depocentres and pinchouts. Both original lithosphere and older stratigraphy are uplifted and eroded by the orogenic front providing new detritus for the basin. This multicyclic development is unambiguously clear in the Bowthorn Block of the northern Mount Isa Basin. Bally (1989) provided an idealised model of this situation that appears to account for most of the data from the Mount Isa Basin (Figure 3-31).

Allen and Allen (1991) calculated maximum foreland basin depths before post-deformational erosion as varying between about 3 km for a low topography "Zagros" style deformation to about 16 km for a high "Himalaya" scale collision. Post-deformation erosion and tectonic thinning can cause massive unroofing of up to 40 km bringing high grade metamorphic rocks to the surface. Hsü (1991) has described unroofing of up to 100 km. Stockmal et al. (1986)

described several geodynamic models of foreland basin development relating the depth of the basin to the height of the mountain range produced during the collision. The preserved foreland depth in the northern Mount Isa Basin is 5 to 7 km, in a total compacted sedimentary thickness of up to 11 km as measured from seismic stacking velocities. This suggests an intermediate Andean scale orogen.

The products of erosion may entirely bypass the foreland basin, since it also will experience uplift due to the regional flexural response of the lithosphere (Allen and Allen, 1991). Klein (1991b), after Angevine and Heller (1987), emphasised that crustal rigidity and heat flow are critical in deciding the foreland basin architecture. Very thick overthrust wedges can also develop with little topographic expression if they are emplaced on a deep oceanic bathymetry. The depth of the foreland sequence in the Mount Isa Basin, the relatively broad (60 km) preserved breadth of basin and the probable scale of the collision involved based on preserved metamorphic grades, all tally with a modest Andean scale collision in the Mount Isa area.

Gravity data can be used to constrain flexural models. Allen and Allen (1991) reported the case of the Ganga Basin in the western Himalaya where the Bouguer gravity anomaly is smaller than expected from the topographic load suggesting that some additional force is pushing upward on the deformed lithosphere. By contrast, the topographic load of the Zagros mountains is insufficient to produce the observed flexure of the Arabian Plate (Snyder and

Barazangi, 1986). This means an additional force is required to flex the Arabian Plate downwards, probably a horizontal compression. Allen and Allen (1991) estimated that flexural rigidities changed by a factor of 5 to 10 (between 1 x 10^{24} and 7 x 10^{24} Nm), based upon work by Lyon-Caen and Molnar (1985). The change in horizontal rigidity across foreland basins suggests that this is not a result purely of convective heat supply or loss in the mantle, but may instead be a result of small temperature changes causing large changes in strength of a highly temperature-dependant lithosphere, or of changes in thickness or composition of the deflected lithosphere. Also in the Ganga Basin, it was necessary to infer a segment of the Indian Plate is now deeply buried beneath the lesser Himalaya, which is steeply dipping and considerably weaker than the segment under the Ganga Basin (about 2-5 x 10^{24} Nm). This is thought to be a common feature of collision zones, since a similar abrupt steepening of the Moho is present in the Carpathian, Appennine, Andean and Zagros mountain belts. The cratonised and deformed Mount Isa Basin is difficult to constrain using gravity models due to the lack of density contrast observed between the basin and underlying basement today, along with the overprinted later deformation.

Allen and Allen (1991) considered that foreland basins are dynamically linked to their associated orogenic belts. The evolution of the orogenic wedge is therefore important and has created the various characteristics of the Mount Isa Basin.

1. The wedge basin shape represents a supracrustal load on the foreland plate with its geometry and structure therefore influencing the deflection of the foreland plate.

2. The shortening and thickening of the wedge, or its extension and forward propagation, change the configuration of the load with respect to the deflected plate, i.e. its magnitude and distribution over the deflected plate.

3. The unroofing by tectonic uplift and erosion of the orogenic wedge provides the detritus for deposition in the basin.

Allen and Allen (1991) recognised three possible driving mechanisms involved in the evolution of orogenic belts. They are: gravity sliding in the form of normal stress on an inclined surface, gravity spreading in the form of plastic movement away from an orogenic high, and horizontal push produced by compression along convergent plate boundaries. Allen and Allen considered the later to be primarily responsible for the dynamics of orogenic wedges. Depending on the geometry of the orogen in relation to the peripheral bulge, gravity sliding from either the orogen or feather edge, could be significant especially in overdeepened basins.

Platt (1986) predicted evolutionary patterns of deformation in an orogenic wedge resulting from externally imposed changes in geometry. The two most important changes recognisable are frontal accretion and underplating. Frontal accretion is the accumulation of material at the feather end of the wedge, thereby lengthening the wedge. The response, if longitudinal underplaying stresses are large enough, will be shortening of the wedge by thrusting. Underplating is the addition of material to the underside of the wedge, resulting in thickening of the wedge and an increase in surface slope. The wedge may respond by extension, lengthening the wedge and lowering surface slopes. Allen and Allen (1991) included two other factors that can influence the shape of orogenic wedges. These are erosion at the rear of the wedge where the highest terrain occurs. This erosion encourages renewed shortening and changes in the basal shear stress, causing shortening and thickening of the wedge. The latter may be due to an increase in the rate of subduction. Allen and Allen (1991) concluded that the implications of the dynamic development of foreland basins are that variations in the rate of subduction, magnitude of compression or material properties of the wedge may cause large temporal variations in the load configuration and therefore in the deflection of the plate. In particular, lengthening and contraction of the wedge, will have an impact on the position of the forebulge on the downgoing slab relative to the orogenic front (Tankard, 1986). In the Mount Isa Basin the peripheral forebulge is believed to be the Murphy Inlier. This is evident from both the seismic sections (Figure 3-29a) and the shallow water Mount Isa Basin sedimentation on the Inlier which remains flat lying today (Plate 6, a).

Complex unconformities can result from the passage of the flexural forebulge (Anadon et al. 1986; Karner, 1986; Heller et al., 1988), however, progressive onlap is the most commonly observed feature. A typical situation is the migration of depocentres and of feather-edge pinchouts. This gives an impression of the mobility of the distributed loads and/or variations in the lithospheric response. In an extreme situation, if the pinchout migration rate far exceeds the rate at which the mountain belt advances, the foreland basin should progressively widen with time. Both the Cordilleran (Rocky Mountains; Dickinson, 1979) and Appalachian foreland basins (Dewey and Kidd, 1974; Denison, 1989) of North America originated by thrusting onto previously stretched passive margin ramps. Subsequent tectonic thickening with little cratonward propagation is thought to be associated with overdeep, shale-dominated basin development together with uplift along the basin-margin arches. A large volume of fine grained clastics and basin margin uplift and erosion are features of the northern Mount Isa Basin that may be explained by overdeepening.

Many basins, and particularly a number that are prolific petroleum producers, illustrate traits of more than one basin type. To some degree they are composite in character changing as external plate tectonic conditions dictate. Many sedimentary cycles punctuated by long standing hiatuses with fundamental changes in tectonic style can occur (e.g. Dickinson, 1977). These may be represented, for example, by basins simply ending with a thermal sag phase or sag basin sequences with superimposed rifting, strike-slip or foreland development. The Persian Gulf is a region where the combination of plate boundaries and movements has produced a composite multicyclic peripheral foreland basin and this appears to be the situation also for the Mount Isa Basin. Basin and craton evolution of the type observed in the Mount Isa Basin is well documented by both Leighton and Kolata (1991) and Klein (1987).

Tectonic controls

Cas and Wright (1987) described the relationship between various types of volcanism and tectonic setting. Because ancient volcanic successions have been affected by both deformation and the chemical overprints of metamorphism and alteration, they concluded that volcanism is more definitively characterised by regional tectonic setting rather than geochemistry. Unfortunately, the reverse situation of deciding regional tectonic character from the volcanic products contained within a basin is rather more speculative despite the work that has been applied to the problem (e.g. Smith and Smith, 1976). Based upon the conclusions of Cas and Wright (1987), Table 3-7 presents the range of possible alternatives applicable to the Mount Isa Basin.

The extent of rift volcanism in the Mount Isa Basin is difficult to determine outside the Bowthorn Block due to the lack of stratigraphically meaningful outcrop. The stratigraphic compilation of Blake (1987) in the Mount Isa area (both Eastern and Western successions) adds up to over 40 km of maximum thicknesses, but only 15 km is present based on the maximum metamorphic grades. Consequently the extent of the volcanic (and clastic) sequences in that part of the basin may have been significantly overestimated when compared to the Bowthorn Block and Riversleigh Fold Zone where 2 km of basal volcanic and volcaniclastic section can be reliably determined. In addition, throughout the northern Mount Isa Basin, the basal volcanic unit is relatively uniformly thick unlike the overlying carbonate and clastic packages.

The composition of the volcanic rocks in the Mount Isa Basin ranges through tholeiitic basalts, felsites, dacites, trachytes to rhyolites. They occur as subaerial lava flows, ignimbrites and tuffs intercalated with a wide range of clastic sedimentary rocks. From Table 3-7 early broad continental rifting or back-arc volcanism appear equally plausible to account for the volcanic composition of the earliest deposition in the Mount Isa Basin. However, based on the Wilson Cycle and seismic evidence of early lithospheric stretching, it is most likely that the basin was initiated by rifting. Geochemical data from the Eastern Creek Volcanics (Wilson, et al., 1985) supports the early rift model.

Volcanic setting	Expected volcanic products
Marginal sea, back-arc basin, interarc basin, spreading volcanism behind oceanic island arcs	Ophiolitic stratigraphy, volcaniclastic layers, regionally extensive arc succession, modern marginal basins are hundreds of kilometres long and wide but may narrow down to converging apices, variable deformational styles, back-arc and interarc basins can have on-land extensions or equivalents floored by ensialic continental crust
Young island arc volcanism associated with oceanic trench subduction zones	Basalts and basaltic andesites of "island arc tholeiite" character derived from the subducting lithosphere and/or the overlying mantle and crust, basement is oceanic lithosphere with arcs tens to hundreds of kilometres wide and several hundred kilometres long, the line of active volcanos is less than 50 km wide, arc polarity reversals may occur, recognition of ancient island arc systems within orogenic belts is difficult
Continental margin arc volcanism associated with oceanic trench subduction zones	Crustal involvement in magma genesis evident from the high proportion of silicic volcanics, including ignimbrites and contemporaneous granitoids, volcanics are largely calc-alkaline, arc and back-arc sediments are continental, forearc sediments are deep marine, shallow marine and continental, the volcanic arc will be hundreds of kilometres long and tens of kilometres wide but may migrate to produce a time transgressive belt of volcanic rocks, complexly deformed forearc accretionary wedge, all associated with sialic basement
Intra-plate continental (flood) volcanism	Alkaline to tholeiitic and more differentiated rocks including trachytes, interpreted in terms of passage of a lithospheric plate over a mantle hot-spot or intraplate extension, erupted upon a stable continental rock record, regionally extensive and overlying continental sialic basement
Continental rift volcanism (narrow linear zones including aulacogenes)	Mafic to silicic and alkaline to peralkaline volcanics (ignimbrites, lavas, pyroclasts and epiclasts), initial subaerial setting with fluvial, alluvial, fan and lacustrine environments, normal-fault-controlled topography, basal section contains thick volcanics or volcaniclastics that become less common up-sequence as the rift widens into a narrow sea, mixed basaltic to silicic volcanics and volcaniclastics or basement derived, immature lithic sediments, or both, should become increasingly mature, more quartz-rich, and may give way to marine carbonates, failed rifts or aulacogenes could cease to develop at any stage
Continental rift volcanism (broad rift zones)	Basaltic, acidic and intermediate rock types ranging from alkaline to tholeiitic to calc-alkaline (bimodal), several hundred kilometre wide zones, basaltic dyke swarms, associated granitoids, multiple localised structurally controlled sedimentary basins

Table 3-7. Alternative volcanic settings for Mount Isa Basin volcanic and volcaniclastic rocks (from Cas and Wright, 1987)

On a global scale, the present sinuous world rift system is an interconnected network of linked segments, and the two principal orogenic belts follow portions of two great circles (Figure 3-17). As can be seen from this diagram, world-wide rifting and orogenesis are related, but for the most part are geographically separated occurrences with little chance of close association except by relative plate movement reversal.

Cross (1986) outlined the following general tectonic controls of foreland basin subsidence in the western USA:

1. Timing of igneous activity.
2. Contrasting styles and loci of deformation along the foreland and thrust belt.
3. The development and maintenance of the rigid lithospheric block.
4. The timing and geometry of subsidence in the foreland basin.
5. The extent of subsidence beyond the foreland basin.

The history of igneous activity in the Mount Isa Basin was summarised by Blake (1987). Intrusions occurred before, during and after the deposition of the sedimentary section (Figure 3-6). In some areas, basement to the Mount Isa Basin comprises intrusions into pre-existing sialic lithosphere. Many mafic dykes were intruded into the sedimentary sequence both before the achievement of maximum burial depth and after the cessation of deposition within the basin in the Mount Isa area, possibly due to late-stage relaxation (Figure 3-18).

Evidence of the regional compressional stress field can be generated from local structures by superimposing them on enhanced regional Landsat, gravity and magnetic images to deduce rigid blocks and stress directions. For the Mount Isa Basin these stresses are shown in Figure 3-13 described previously.

The timing and geometry of foreland subsidence in the Mount Isa Basin is demonstrated by the Bowthorn Block seismic data. Evidence for syn-depositional compression and changes in loci of deformation along the foreland belt can be interpreted from the unconformities and the major sedimentary dip directions that indicate the flexural depocentres within the basin. The major depocentres in the northern Mount Isa Basin were to the south during the initial phase of foreland sedimentation, and to the southwest during the final phases of deposition in the basin.

Eustatic sea level changes

Sea level change is the cumulative effect of many factors and its occurrence is difficult to distinguish from tectonic effects in local areas. This is particularly important for the Proterozoic where the lack of data has prevented the establishment of sea level curves.

Allen and Allen, (1991) described four factors which influence global sea level change. They are:

1. Continuing lithospheric differentiation due to plate tectonic processes, (this should cause long term fluctuations);

2. Changes in the volume of ocean basins caused by sediment accumulation or sediment abstraction;

3. Changes in the volumetric capacity of the ocean basins caused by volume changes in the volume of the mid-ocean ridge system; and

4. Changes in the volume of sea water due to ice caps and glaciers.

There are two significant probable effects of eustatic sea level changes on the Mount Isa Basin. These are unconformities and erosional truncations producing sequence boundaries within the sedimentary section of the basin, and changes to the hydrodynamic regime within the basin. The former effect may be evident on the seismic data (although syndepositional tectonism seems the most likely cause of the onlap sequences observed) while the latter was probably responsible, at least in part, for brine transport within the basin. Each cause is difficult to attribute solely or even primarily to eustatic as opposed to tectonic controls, particularly in an asymmetric foreland basin where rapid basin subsidence is common. The major difference between the two effects is in the nature and geometry of sedimentation above the unconformity surface. Deep water sedimentation showing pronounced asymmetric thinning away from thrust faults and above an unconformity surface is most probably the product of tectonic subsidence within the basin. This appears to be the situation in the northern Mount Isa Basin.

Hamilton (1987) attributed the copper-zinc mineralisation in the Red Sea region to the movement of mineralising fluids due to a rapid sea-level rise at the end of a sea level low stand and this could equally apply to both hydrocarbon migration and mineralisation in the Mount Isa Basin although the foreland geometry of the basin suggests that tectonic driven brines along the lines suggested by Bethke (1990) for the Arkoma Basin were more important.

Climatic factors

Lithostratigraphy within the basin can provide evidence of the prevailing climate at the time of deposition as climate may significantly influence basin fill (Klein, 1991c). Based on work by Ziegler et al. (1984) shallow water carbonate distribution on the earth today occurs between 35° north and south. This implies that much of the deposition within the Mount Isa Basin took place between those latitudes provided average global temperature and the Earth's obliquity have not changed significantly. Global wander patterns for the Palaeo to Mesoproterozoic of Australia confirm relatively low latitudes for this period (Idnurm and Giddings, 1988).

The oldest known glacial deposits occur at around 2.5 Ga (Stanley, 1986). Reduction in global temperature to produce ice ages depends on many factors, but particularly the radiant output of the sun and the circulation of oceanic waters. The absence of continents at or surrounding the poles would inhibit global ice formation and alter the latitudes of potential reefal carbonate build-ups. Therefore it is difficult to conclude much about the palaeoclimate of the Mount Isa Basin other than that major or minor carbonate build-ups formed during each of the rift, drift and peripheral foreland phases of the basin's evolution possibly suggesting a relatively temperate to warm climate throughout.

Provenance controls

Dickinson (1988) described a technique of using provenance interpretations to test alternate palaeogeographic and palaeotectonic reconstructions. Sediment shed into basins records rock masses removed by erosion from orogenic highlands. Where sediment dispersal paths between orogenic provinces and adjacent sedimentary basins are short, stratigraphic variations in sandstone petrofacies offer an effective means to monitor the tectonic evolution of the orogen through time. Most sediment-laden rivers, however, that deliver large volumes of suspended load sediment to the ocean typically begin in collisional orogens and pursue longitudinal courses, either within orogenic highlands or along the axes of adjacent foreland basins. Northerly, easterly and westerly transport directions have been inferred in the Myally region of the Mount Isa Basin (Wilson and Grimes, 1984). In the Lawn Hill region, Hutton and Sweet (1982) recorded common easterly, southeasterly and northerly palaeotransport directions from cross-bedding measurements. While a large range of transport directions may be inferred from this data, all these measurements must be considered in the context that the region contains many faults that could locally alter the regional patterns.

Working on the rift phase of the southern Mount Isa Basin, Bultitude (1982) described the Yappo Member at Ardmore as fluvial to shallow marine outwash fan deposits. Meta-arkoses and feldspathic meta-arenites in the upper part of the unit consist mainly of coarse debris, probably derived from a granitic landmass. The presence of conglomeratic metasedimentary rocks containing many felsic metavolcanic clasts in the Eastern Creek Volcanics, and the absence of such clasts in the upper part of the underlying Mount Guide Quartzite, indicate that the onset of basaltic volcanism was accompanied by some tectonism and uplift of source regions.

Provenance in the passive margin phase of the northern Mount Isa Basin was primarily intrabasinal resulting from large scale shallow-water carbonate build-ups.

During the foreland phase of basin sedimentation a northerly direction of transport prevailed based on both seismic data from the Bowthorn Block and palaeocurrent measurements from outcrop adjacent to the Murphy Inlier. Palaeocurrent directions determined by Neudert (1983) suggest a predominant northerly transport direction for the Upper Mount Isa Group near Mount Isa.

3.4.7 Basin analogues applicable to the Mount Isa Basin

The purpose of this section is not to describe in detail all aspects of the many, well documented, foreland basins in the world similar to Mount Isa, but rather to highlight their characteristics relevant to the Mount Isa Basin. Each analogue studied is predominantly a peripheral foreland or associated polyhistory basin, but with its own characteristics.

The Middle East Province (Multicyclic Basin)

The regional picture of the Middle East is rather simple by contrast with many other regions of the world. Because of both the climatic setting and the low scale foreland Zagros mountain development, the basin sedimentary pile is both thin and carbonate dominated. The superlative hydrocarbon producing character of this basin (it contains 57% of the worlds known oil, Shannon and Naylor, 1989) probably relates to the excellent and prolific source rocks combined with the relatively gentle hydrodynamics in such a system.

Compared to the Mount Isa Basin, the Middle East succession comprises a much larger proportion of evaporates and carbonates with far fewer early rift sequence rocks. Because the Middle East Basin is thin, the palaeotopography of the Zagros foreland mountain belt was probably a few kilometres less than that of the Andean scale topography at Mount Isa. The major difference probably relates to the hydrodynamic and geothermal capacities of the Mount Isa Basin to pump fluids from 10 to 15 kilometre depths. At a world average geothermal gradient of 30°C per kilometre, fluid temperatures of 300 to 450°C were possible even without any intrusions.

Edwards (1992), in his review of the Middle East, considered the absence of prolonged erosional intervals, strong tectonism or metamorphism as significant contributing factors to the petroleum potential of the area.

Papuan and Carpentaria Basins

Hebberger (1992) described the regional elements of the Papuan Fold and Thrust Belt beginning with late Triassic rifting that produced the probable source rock for the major oil fields in the basin. Passive margin, and later foreland development, provided the fluid migration pathways and host rocks for the major traps.

Jaques et al. (1978) described the occurrence of tholeiites from the Marum ophiolite complex in northern Papua Guinea. Davies (1971) considered a peridotite-gabbro-basalt complex in eastern Papua was an overthrust plate of oceanic mantle and crust and Connelly (1979) described the emplacement of the Papuan Ultramafic Belt as typical of this style of basin. Many details of the variety of igneous rocks associated with the Papuan Basin are reported in various papers in Hughes (1990). The various igneous compositions reported from within and near the Papuan Basin suggest that a range of intrusive and volcanic products could potentially be deposited or reworked into the peripheral foreland sequence and the basin generally.

Although geographically distant and cratonward, the Carpentaria Basin described by McConachie et al. (1990a and b) is continuous with the Papuan Basin, but is intra-cratonic in style. The basin was probably initiated by compressional flexure during the late Jurassic. Seismic data over the Carpentaria Depression shows major easterly dipping thrust faults in basement and these cut the oldest Carpentaria Basin rocks.

Only a small proportion of the sedimentary rocks of the Carpentaria Basin are believed to have been sourced from Papua New Guinea with the majority derived from the Coen Inlier and local highlands. Middle Triassic sequences have been recognised as far south as Boomarra and may underlie the offshore Carpentaria Basin. The relationship between the Papuan and Carpentaria Basins is very similar to that of the Mount Isa and McArthur Basins. The comparison is similar to the structural connotations of the old eu-miogeosynclinal division, where intracratonic basins were almost an extension of the mio-geosynclinal setting, as observed between the Arkoma and Illinois Basins.

Western Canada Basin (Alberta Foreland Basin)

Hitchon (1984) described the geothermal gradients, hydrodynamic gradients and hydrocarbon occurrences of the Alberta Foreland Basin. Tilley et al. (1989) reported the thermal history of the Alberta Foreland Basin based on fluid inclusion data and vitrinite reflectance measurements. Each of these studies compares closely with the known information from the northern Mount Isa

Basin and from other asymmetric foreland basins e.g. the retroarc Bowen Basin (McConachie, 1986b), where vitrinite reflectance measurements show rapid change across the basin.

The drift phase carbonates within the lower part of the Western Canada Basin were relatively unfaulted during deposition and thus provide an excellent reference for section balancing (Dr. J.D. Edwards, pers. comm., 1992). This contrasts with the northern Mount Isa Basin where down away-from-basin growth faults formed during both the rift and drift phases.

The organic geochemistry of Pine Point, a major lead-zinc deposit in the Alberta Foreland Basin, was described by McQueen and Powell (1983). This deposit is situated nearer to the basin margin than the major oil fields. This suggests that the high temperature brines that transported the lead and the zinc from the deep basin to the site of deposition, by-passed the oil and gas fields due to a change in the basin plumbing system.

The Eastern Venezuela Basin

The Eastern Venezuela Basin occupies a similar structural setting to the Alberta Foreland Basin. This prolific oil producing basin exhibits down out-of-basin faults in drift phase carbonates at the base of the sedimentary sequence as illustrated by Barker (1985). This same structural characteristic is observed in the northern Mount Isa Basin.

Appalachian-Allegheny Basin

Stanley (1986) in his cross-section and schematic of the Appalachian Basin (Figure 3-19) showed the typical valley and ridge development in this kind of structural setting which is very similar to the fold development around Mount Isa.

Hoagland (1976) illustrated the basin model for the development of the Tri-state MVT lead-zinc deposits in regional karstic carbonate aquifers. Although both clastic- and carbonate-hosted deposits occur in this basin system, the preponderance of carbonate hosted deposits suggests widespread karst was the regional aquifer system in this basin, unlike the Mount Isa Basin where the clastic turbidite channel sandstone sequence appears to be the major host for mineralisation.

The Arkoma Basin (Arkansas-Oklahoma)

The Arkoma Basin in the southern USA is very similar to the Mount Isa Basin. The Arkoma Basin is a major gas province (Branan Jr, 1968). The structure of the Ouachita Orogen (Lillie et al., 1983) has been traced and studied using seismic and other data from the Appalachian Belt in the east to Texas in the west (Culotta et al., 1992).

The main features of this basin that appear applicable to the hydrocarbon prospectivity of the northern Mount Isa Basin are:

1. Most of the gas production is located on a relatively undeformed zone that is analogous to the Bowthorn Block of the northern Mount Isa Basin. This area is clearly shown in the data of Lillie et al. (1983).

2. Most producing zones in the Arkoma Basin are contained within large stratigraphic traps, and are not related to the structures within the basin (Houseknecht and McGilvery, 1990). The gas fields occur in areas where early emplaced oil was cracked by hot brines that migrated through the basin. Apart from cracking the reservoired oil, these brines matured the existing source rock producing supermature vitrinite levels. Gas fields in the Arkoma basin contain vitrinite that exhibits reflectances up to 3.5% R_o (Hathon and Houseknecht, 1987).

3. The acoustic velocities of the rocks of the Phanerozoic Arkoma Basin are similar to those in the Mount Isa Basin. This suggests that once diagenesis and lithification reach a certain stage negligible further compactional changes occur.

Several papers show seismic lines and cross-sections from the Arkoma Basin (Vanarsdale and Schweig, 1990; Blythe et al., 1988; Lillie et al., 1983), but the best example (believed to be from the buried extension of the thrust front in east Texas) is shown in Figure 3-20. This section has remarkably similar structural character and sequence stratigraphy to the northern Mount Isa Basin seismic sections.

Morris (1974) and Sutherland (1988) described the depositional history of the Arkoma Basin in the foreland stage of the basin evolution. They observed palaeotransport directions from both the foreland and the peripheral bulge sides of the basin with common axial depositional systems. Leach and Rowan (1986) recognised a genetic link between Ouachita foldbelt tectonism and the Mississippi Valley-type lead-zinc deposits of the Ozarks.

Plate tectonic models for the Arkoma Basin evolution have been produced and described by several authors (Wickham et al., 1976; Houseknecht, 1986; Klein, 1991e). These clearly show the passive margin to foreland history, but it is obvious that unlike the Mount Isa Basin, the Arkoma Basin contains very little rift phase sedimentation within its sedimentary section. The Arkoma Basin passes cratonward into the cratonic Illinois Basin.

3.4.8 Proterozoic foreland basins

The Wopmay Orogen of Canada formed along the margin of an early continent that developed between about 1.8 and 2.1 Ga, over a large area known as the Slave Province now approximately 100 km west of Hudson Bay. The Wopmay Orogen is a well documented example of a Proterozoic foreland basin described by Hoffman (1980). In the words of Stanley (1986), it was "a modern style of orogeny" that is exposed along the low-lying surface of the Canadian Shield because of continental glaciation that has repeatedly scoured the orogenic belt over the last 2 Ma.

Structural and lithostratigraphic cross-sections from Stanley (1986) based on Hoffman (1973) are presented in Figure 3-21. These are similar in both lithostratigraphy and structure to the Mount Isa Basin.

Stanley (1986) cited two kinds of evidence that the Proterozoic Wopmay Orogen had the same pattern of formation as Phanerozoic (modern) orogenic systems. First, the parallel igneous, metamorphic, and fold-and-thrust belts resemble similarly arranged belts of younger mountain ranges. Second, within the fold-and-thrust belts, shallow-water shelf deposits are succeeded by flysch deposits that give way to molasse. The presence of failed rifts elsewhere in northern Canada is also evidence that modern plate tectonic processes were operational in the Proterozoic. Such features as the Proterozoic North American Midcontinent Rift (e.g. Cannon et al., 1989) are more dubious, however, as there is little clear tied seismic and well data and the sequences appear far too thick to be conventional rifts. Hill and Campbell (in press) have proposed a migrating hot spot track model for the Midcontinent "rift".

It seems likely that the westward-facing edge of the Slave craton, along which the Wopmay Orogen formed, came into being at about 2 Ga, when a rift system broke apart a slightly larger continental mass. Almost simultaneously, the two rifts that later failed began to form at right angles to the newly forming shelf edge. Shortly after that, the shelf edge must have foundered when it was rafted up against a subduction zone. Then, as can be observed from Phanerozoic orogens, igneous activity elevated the crust seaward of the shelf edge, and mountain building began. This orogenesis produced a retroarc foreland basin called the Great Bear Magmatic Zone which has been described by Hildebrand et al. (1987). The magmatic zone preserved today is 100 km wide and 900 km long. Volcanism was of Andean type and presumably a peripheral foreland basin developed to the west. Plate tectonic reconstructions by Moores (1991) based on the entirely separate relationship between Antarctica and North America, suggest this may have been the Mount Isa Basin (see Section 3-11, Plate tectonic model and Figure 3-38).

To the east of the Wopmay Orogen, and northeast of the Slave Province, lies the Kilohigok Basin, an early Proterozoic (1.9 Ga) basin described by Grotzinger and McCormick (1988). The Kilohigok Basin originated primarily in response to flexure of the lithosphere during emplacement of loads, and forms a typical foreland style basin. Despite Gottzinger and McCormick's comment that the lack of suitable biostratigraphic age constraints for Precambrian sequences precludes the application of detailed quantitative modelling, their "first order" attempt based upon outcrop lithostratigraphy and structure, revealed many details. The work showed that lithospheric flexure occurred during basin subsidence in the Palaeoproterozoic.

3.5 CHRONOSTRATIGRAPHY

Figures 3-6 and 3-10 present the major age determinations within the Mount Isa Basin. Geochemical age calculations within the Mount Isa Basin are of limited value for stratigraphic control because of the wide error bars associated with each analysis. Despite this it is still possible to obtain dates that characterise the major sequences within the basin. They are 1800 to 1700 Ma for the rift phase, 1690 to 1670 Ma for the passive margin and 1610 to about 1600 Ma for the foreland sequence.

With such coarse age control the only practical system of relative age dating is the "Principal of Superposition". Additionally the possibility exists that active sedimentation in the basin did not extend much into the Mesoproterozoic as dating of the final phase of sedimentation is based on dykes in the Roper Group of the McArthur Basin that could be much younger than the intruded foreland sequence.

3.6 BIOSTRATIGRAPHY

Several preliminary attempts have been made to establish Proterozoic age dating techniques based on stromatolites and algae (acritarchs), but these are not sufficiently well defined or catalogued (Peat et al., 1978) to enable comparative sequence dating of the type available using Phanerozoic biostratigraphy.

3.7 LITHOSTRATIGRAPHY

3.7.1 Background

The stratigraphy of the northern Mount Isa Basin sequence and its correlation with the McArthur Basin, is illustrated in Figure 3-9. The equivalence of the major lithostratigraphic groups is shown in Figure 3-22. This is a regional cross-section from north to south along the line of section shown on Figure 3-23 across the Murphy Inlier. Lithostratigraphic correlations within the Mount Isa Basin are shown in Figure 3-6.

Lithostratigraphic correlation is very difficult within the Cloncurry Orogen and the Riversleigh Fold Zone due to the fault disruption within the basin and the lack of detailed age determinations. One possibility for age control could be to apply the techniques described by Ryer et al. (1980) to the altered volcanic ash falls that have been recognised at Mount Isa and Century. Dr. R.W. Page of AGSO is currently attempting to date these rocks.

The work presented in this section of the thesis is a compilation of the available literature augmented by direct observations made during several field reconnaissance trips and structural mapping programs that were reported by Dunster and McConachie (1990) and McConachie et al. (1991b). Thin section studies were undertaken by Moultrie (1991a, b and c) under my supervision.

Substantial interpretation changes that have occurred since those reports were compiled have been incorporated in this description.

The nomenclature and definitions of many lithostratigraphic groups in the southern Mount Isa Basin were described by Derrick et al. (1976a-e), Derrick et al. (1980) and Sweet (1981).

The results of the 1992 Comalco 423P petroleum exploration drilling are reported in Section 3.7.3, The Riversleigh Fold Zone and southern Bowthorn Block, because the work was undertaken far enough into the basin where the stratigraphy had thickened so as to make the nomenclature at the northern basin margin difficult to apply. Unfortunately, the various lithostratigraphic packages are not neatly confined to the various structural blocks that can be identified today.

3.7.2 The northern outcrop margin of the Bowthorn Block

The lithostratigraphy of the basal volcanic rocks and the Fickling Group (upper and lower) is illustrated in Figure 3-24.

Basal volcanic rocks

Wire Creek Sandstone (Pti)

At the northern margin of the Mount Isa Basin, the Wire Creek Sandstone unconformably overlies the Nicholson Granite Complex, Cliffdale Volcanics, and Murphy Metamorphics. It is conformably overlain by the Peters Creek Volcanics. In the headwaters of Wire Creek, the sandstone forms a series of rugged dissected ridges. Extensive jointing is visible on aerial photographs. Sweet et al. (1981) described medium to coarse grained sandstone with scattered granules and pebbles, mostly of quartzite. Conglomeratic beds are common only east of Wire Creek. Silicification appears to be pervasive. Near Gorge Creek, the unconformity on basement at the base of the Wire Creek Sandstone can be clearly seen on aerial photographs. Outcrop was examined on the ground on the road leading west to the border, and near the Queensland/Northern Territory border fence track. In both cases the outcrop consists of silicified cross-bedded reddish brown sandstone with sporadic well rounded pebbles, mainly quartzite. Scree covers the actual contacts.

Sweet et al. (1981) noted the presence of large clasts of tabular brown quartzite in both the Wire Creek Sandstone and the Westmoreland Conglomerate (its equivalent in the McArthur Basin) and suggested that older Precambrian was being worked into the Wire Creek Sandstone. Sweet and Slater (1975) described other contributions from the Nicholson Granite Complex in the west.

Seismic data did not indicate the presence of an older metasedimentary or sedimentary sequence that could have been reworked by the Wire Creek Sandstone although metasedimentary rocks are present within the Murphy Inlier.

Based on outcrop observations, the Wire Creek Sandstone has virtually no reservoir potential.

Peters Creek Volcanics (Ptp)

The Peters Creek Volcanics conformably overlie the Wire Creek Sandstone and are overlain with angular unconformity by the Fish River Formation. The contact between the volcanics and the Fish River Formation is exposed in Wire Creek (Plate 5, a). The erosional contact with the Fish River Formation has removed progressively less of the volcanic rocks towards the east. This angular unconformity is visible on some seismic sections.

Sweet et al. (1981) mapped eight members within the volcanic sequence, of which only the Buddawadda Basalt Member is formally named. The volcanic rocks are well exposed in Wire Creek. The various members are easier to distinguish on aerial photographs than on the ground and consist mainly of basalts and rhyolites.

The named member of the volcanic succession, the Buddawadda Basalt Member, designated Ꞓtp$_{1b}$, was described by Sweet et al. (1981) as a series of thin vesicular and amygdaloidal tholeiitic basalt flows with a thin fine grained silicified sandstone interbed near the top of the unit. The basalt member is at least 600 m thick at Wire Creek, but thins to both the east and west. (Units a and c to h were unnamed).

The basalt is overlain by unit Ꞓtp$_2$ which consists of massive pink to reddish brown rhyolite. It forms rugged dissected ridges on Wire Creek. The unit is extensively jointed, both at outcrop and aerial photograph scale. Sweet et al. (1981) estimated a thickness of between 300 m and 500 m for Ꞓtp$_2$.

Unit Ꞓtp$_3$ is absent west of Hedleys Creek and covered by alluvium over much of its outcrop zone to the east. Sweet et al. (1981) described it as silicified mudstone overlain by dolostone and silty dolostone. Oolites, laminations and stromatolitic structures are preserved. Halite casts occur in the siltstone. The unit is about 180 m thick, but thins to the west. Interestingly, several workers before Sweet et al. (1981) regarded this unit as an outlier of sedimentary rock equivalent to the Walford Dolomite resting unconformably on the volcanic rocks, not intercalated within them. The current field inspection work supports the interpretation of Sweet et al. (1981).

The unit $Ꝑtp_4$ crops out poorly along Wire Creek and forms low relief country away from the creek. It consists of rhyolites, rhyodacites and minor tuff and sandstone.

In contrast, unit $Ꝑtp_5$ forms rugged ridges with extensive bedding plane partings in the creek. Locally extensive joints are visible on aerial photographs and these may be evidence for post-Mesozoic reactivation of faults. Lithologically, $Ꝑtp_5$ consists of massive reddish brown porphyritic rhyodacite and rhyolite. Its thickness ranges from 200 to 350 m dependant on two factors. Firstly, the upper contact with overlying volcanic rocks in the east shows up to 50 m of palaeorelief on the top of $Ꝑtp_5$, and secondly $Ꝑtp_5$ is eroded by the Fish River Formation in Wire Creek.

Units $Ꝑtp_6$ and $Ꝑtp_7$ are absent west of Hedleys Creek having been eroded before the deposition of the Fish River Formation.

Lower Fickling Group

The lower Fickling Group consists of two formations – the Fish River Formation and Walford Dolomite. The upper Fickling Group comprises the Mount Les Siltstone and Doomadgee Formation.

The Fish River Formation (Ꝑff)

The Fish River Formation is the least well documented formation in the Fickling Group and consists predominantly of sandstone (Ꝑff$_1$ and Ꝑff$_3$) with a shale marker horizon (Ꝑff$_2$) roughly two thirds of the way up the formation. It was deposited on a marked unconformity surface cut into all units from the Peters Creek Volcanics to the Nicholson Granite Complex and overlies progressively older rocks westwards, indicating greater uplift and erosion in the west than in the east. This unconformity at the base of the Fish River Formation (the breakup unconformity, Plate 5, c) was interpreted on seismic sections, but not confirmed by drilling due to its lack of economic importance for petroleum exploration.

In Wire Creek, the Fish River Formation consists of a basal boulder to pebble conglomerate containing quartzite and volcanic clasts overlain by medium grained quartz sandstone (Ꝑff$_1$). Cross-bedding and ripple marks are ubiquitous. Cross-bedding shows large variations in angle, ranging from very low to quite high. Ripple marks also show considerable variability including starved asymmetrical, symmetrical, truncated and large forms approaching hummocky cross-stratification. The ripples appeared to switch direction repeatedly through 90° up the section. Flute marks and other problematic current features of the type described by Grey and Williams (1990), were also seen. Possible synaeresis cracks at several scales (Plate 6, b) and centimetre thick shale interbeds with textures reminiscent of thinly bedded evaporites were also observed.

The sandstones contain a 50 m thick unit of flaser bedded laminated micaceous purple and green shale (Ᵽff$_2$) with minor fine sandstone. This unit is partly faulted out in Wire Creek by a fault that is parallel to and less than a kilometre from the Fish River Fault Zone as mapped by Sweet et al. (1981). Wire Creek follows this fault for some distance. The fault and the displacement of Ᵽff$_2$ are clearly visible on aerial photographs. The faulted exposures in the creek form a quite spectacular cliff (Plate 5, b).

Outcrop of the Fish River Formation was also examined north of the Nadjuburra Road near the Queensland/Northern Territory border. Similar sandstone lithologies to those at Wire Creek are exposed as a 30 m high cliff. The shales crop out in a small fault-bounded block in Gorge Creek located between Wire Creek and the border.

The total thickness of the Fish River Formation near Wire Creek is about 200 m to 250 m, but it thins farther west and may pinch out entirely in the Northern

Territory. The sandstones are entirely silicified in outcrop and are quartz-rich in composition. Somewhat surprisingly, given the extent of the silicification, the Fish River sandstones do not exhibit jointing on aerial photographs (Dunster and McConachie, 1990). The Fish River Formation is regarded as having only limited reservoir potential unless diagenesis is significantly less pervasive in the subsurface. The source potential of the shales is considered poor based on the obvious lack of organic matter.

The basal Fish River Formation was probably deposited in palaeo-valleys during the early phases of a marine transgression. The basal conglomerate may represent fluvial sediments, marine sediments or marine reworking of original fluvial deposits.

The presence of cross-bedding, alternating ripple marks and possible synaeresis cracks higher in the formation suggest a shallow marine tidal-flat possibly with intermittent fluvial sheet flow. The variety of cross-bed angles and ripple forms indicate variations in current strength that would not be expected in a purely tidal environment. The environment of deposition of the Ƥff$_2$ shales was possibly lacustrine or shallow marine with tidal scouring and oxidation of the rocks by penecontemporaneous weathering.

Walford Dolomite (Pfw)

Northwest of Walford Creek, the Walford Dolomite is spectacularly exposed in flat lying outcrop on the Murphy Inlier. Preservation of Magadi (or Coorong) type mudcracks with cauliflower chert pseudomorphs after evaporites (all in their original attitudes) clearly show the lack of post-depositional deformation in the Bowthorn Block of the northern Mount Isa Basin (Plate 6, a and c).

The Walford Dolomite originally consisted of stromatolitic, oolitic and intraclastic dolostone with minor siltstone and sandstone interbeds (Plate 6, d). Almost all of the formation has undergone some degree of silicification. Much of the outcrop is entirely chertified and thin sections from relatively fresh outcrop and core, also show pervasive incipient silicification (Moultrie, 1990b).

Although the contact between the Fish River Formation and the Walford Dolomite is quite sharp and easily mapped on aerial photographs it does not appear to be disconformable.

The Walford Dolomite is well exposed in a northeasterly trending belt up to 3.0 km wide west of the Calvert Fault and extending in fault bound blocks as far east as Walford Creek. The formation has been mapped in considerable detail and logged in many cored drillholes by at least three mineral exploration companies, and Amoco under petroleum ATP 327P. This study did not duplicate their field mapping, but sought to investigate some more distinctive facies within the Walford Dolomite. Outcrops along the Fish River Fault Zone from Walford Creek in the east to the Queensland/Northern Territory border in the west were examined at points of easiest access. This included outcrops south of Gorge Waterhole, in Gorge Creek near the type section and along the border fence.

In outcrop at the type section, the basal Walford Dolomite has been mapped as a 10 to 20 m thick shale, siltstone and sandstone unit that is overlain by a distinctive horizon of columnar stromatolites with oolitic phases interspersed between the columns. Taylor (1970) referred to this as the "Lower Collenia Marker". Collenia (Plate 7, b) is no longer recognised as a formal genus and the use of Taylor's term should be discouraged. Elsewhere in the type section, oolitic horizons, desiccation and dewatering features and thin intraclastic breccias were noted. Halite casts (Plate 6, e) were identified by this author within half a kilometre of the type section and although not recognised by the Sweet et al. (1981), their presence in other areas was noted by Amoco geologists (Dorrins et al., 1983).

Sweet et al. (1981) considered that the type section does not contain faults (p18), but they showed a nearby northwest-southeasterly trending fault on their map. This fault corresponds to a marked aerial photograph lineament and, being only a few hundred metres from the type section, brings the Walford Dolomite into juxtaposition with the Fish River Formation and Peters Creek Volcanics (Dunster and McConachie, 1990). Consequently it appears that the

400 m thickness for the Walford Dolomite quoted by Sweet et al. (1981) is probably an underestimate even on the northern flank of the basin. The results of the seismic mapping show quite a variable thickness up to 700 m for the Walford Dolomite due primarily to erosion, but also non-deposition in various areas along the northern basin margin.

The track that approximately follows the Queensland/Northern Territory border also affords good exposure of the Walford Dolomite. Several stromatolite forms are exposed. Simple domes and columnar forms are shown in Plate 3, (a, b and d). They occur stratigraphically above and below the distinctive columnar stromatolites mapped as a marker by Taylor (1970). Some examples show that the columnar forms colonised directly on the domal forms. Possibly because of several faults in the area, stratigraphic thickness between the columnar stromatolite horizon and the top of the formation does not appear to match that measured by Taylor (1970) further to the east. Halite hoppers and desiccation features were not observed in outcrop along the border fence. There is, however, evidence of brecciation and minor mineralisation associated with small faults. Open circular vugs and pipes up to 3 cm in diameter were noted and small clints and grikes are well developed in weakly silicified Walford Dolomite (Plate 7, c).

The upper portion of the Walford Dolomite is also well exposed in the area between Lead Hill and Gorge Waterhole on Wire Creek. Well developed domed stromatolites overlie locally abundant halite casts. Crocodile skin texture (Mr J.N. Dunster, pers. comm. 1990; possibly indicative of phosphate, Dr M.D. Muir, pers. comm., 1993) on ripple marks occurs in close association (Plate 7, a). Taylor (1970) mapped an upper columnar stromatolite horizon near the very top of the formation near the type section. Rowley (1983) mapped a sandy facies within the Walford Dolomite east of the type section. This can be traced several kilometres on aerial photographs.

Drillhole intersections of the Walford Dolomite show general similarity to outcrop, but the characteristic columnar stromatolites and halite casts are far less numerous in those portions of the Walford Dolomite that have been cored, making accurate correlations of facies a difficult task. Cores exhibit some differences in environments of deposition. The presence of halite casts, plus dewatering and desiccation features in outcrop support the interpretation of a generally widespread peri-emergent zone with near shore stromatolites and small ooid shoals developed in shallow marine conditions offshore. This picture is well supported by the repeated shallowing-up cycles seen in core from Amoco 83-4. This core contains cauliflower cherts after evaporites, abundant dewatering structures and mud cracked bleached zones. The Esso drillhole Gorge Creek-1 (GCD-1) only a few kilometres to the west-northwest contains more thrombolitic and peloidal fabrics with much less evidence of shoaling up. Core from the latter hole contains more intensive pressure solution (stylolites, stylo-mottles, stylo-nodules, stylo-bands) and evidence of brecciation textures that the Amoco core does not. While the lithostratigraphic correlation between the two wells is obvious, the lack of a corresponding correlation in syndepositional and diagenetic overprints suggest that deposition of the upper Walford Dolomite and possibly the Mount Les Siltstone was diachronous (Dunster and McConachie, 1990). This is further supported by Rowley's (1983) comments on silicification described below.

Rowley (1983) was the first to deal with the relationship between the patchy silicification and mineralisation within the Walford Dolomite, and to include petrographic studies in addition to field mapping (Dunster and McConachie, 1990). Rowley concluded that while the more patchy silicification was obviously secondary, the chertification seen at depth in drill core and most of the intense chertification seen in outcrop resulted from a palaeoweathering event (*i.e.* a palaeo-subaerial exposure surface), thus putting an isosynchronous paraconformity (depositional hiatus) within the upper Walford Dolomite west of the type section and between the Mount Les Siltstone and the Walford Dolomite in the type section itself. This interesting hypothesis, yet unproved, is consistent with the idea of diachronous deposition in the upper Walford Dolomite and the Mount Les Siltstone (Dunster and McConachie, 1990). It raises the following points of relevance to exploration for hydrocarbons:

(i) The subaerial exposure surface may be a time line observable on seismic sections if sufficiently widespread and well developed. It transgresses the lithostratigraphy from intra-Walford Dolomite and possibly formed the Mount Les Siltstone/Walford Dolomite boundary. Several shelfal unconformities and the basal foredeep unconformity mapped from the seismic data strongly transgress the stratigraphy at this level near the northern basin margin.

(ii) Palaeosubaerial exposure of carbonates is usually associated with an increase in porosity and permeability. If silicification is related to subaerial exposure it has occluded, not enhanced, porosity and permeability and would not augur well for reservoir development further into the basin.

Comalco's 1992 petroleum exploration drilling in the northern Mount Isa Basin intersected the top of the Walford Dolomite (Lady Loretta Formation) in both Desert Creek-1 and Argyle Creek-1. In each hole the formation is tight.

Upper Fickling Group

Mount Les Siltstone (Pfl)

The Mount Les Siltstone consists of dolomitic siltstone, being sufficiently fissile in outcrop to be better described as shale, and minor dolostone. The Mount Les Siltstone crops out in a narrow belt up to 1.0 km wide from the Queensland/Northern Territory border almost to Hedleys Creek in the east. Despite being variably silicified in both the surface and subsurface the siltstone weathers readily and outcrop is generally poor. The contact with the underlying Walford Dolomite was generally believed to be conformable if not gradational (before Bowthorn Block seismic data acquisition), although a paraconformity may exist locally. From the Bowthorn Block seismic work it appears that this surface is the basal foredeep unconformity.

The type section in the Gorge Creek area is typically exposed in outcrop along the border fence and in Wire Creek as pale bleached siltstones, commonly present only as surface float. Dolomite interbeds occur more commonly near the top of the formation and fissile dark grey to black carbonaceous siltstone and sandstone crop out in the bank of Wire Creek and in the bank of Gorge Creek near the Gorge Creek Prospect. Drillhole intersections also show several dark carbonaceous horizons and evidence of shallowing up, and desiccation as dewatering structures and mud cracks. Pseudomorphs after gypsum have been reported from the Mount Les Siltstone in the Northern Territory (Sweet et al., 1981). These desiccation overprints testify to repeated subaerial exposure during deposition.

The Mount Les Siltstone is variable in thickness because of erosion during the deposition of the overlying formations, but it appears to have a maximum thickness of 200 m. The type section is about 90 m thick. A recorded interval of 102.53 m was intersected in the Esso hole GCD-2A approximately 3.5 km to the southwest (Billington, 1981a). In the Northern Territory, Billington (1981b) mapped fresh Doomadgee Formation deposited on weathered Mount Les Siltstone showing up to 50 m of relief. A further 3 km southwest in GCD-4 the Mount Les Siltstone is 160.4 m thick and includes two carbonaceous black shale horizons of 71.8 m and 35.0 m in the upper and basal parts of the formation respectively (Rowley, 1983).

Rowley (1983) suggested that the Mount Les Siltstone is consistently thinner towards the east, and cited thicknesses of 55 m near Lead Hill and 58 m in Esso GCD-1. This is believed to be due to erosion at the time of deposition of the overlying Doomadgee Formation, possibly with some uplift on the eastern side of the Calvert Fault before deposition of the Doomadgee Formation. From the seismic work it is evident that a regional basement high is present under Doomadgee.

Comalco's 1988 and 1992 petroleum exploration drilling in the northern Mount Isa Basin intersected units equivalent to the Mount Les Siltstone in all the wells (i.e. Beamesbrook-1, Desert Creek-1, Argyle Creek-1 and Egilabria-1), but more easily related to the Termite Range and Riversleigh Siltstone Formations.

Doomadgee Formation (Pfd)

The Doomadgee Formation is lithologically more heterogeneous than the lower units in the Fickling Group and could be remapped as several formations. The lower contact of the Doomadgee Formation appears to be locally conformable in outcrop, but the composition of clasts within the basal conglomerate in the west suggests that it may rest unconformably on Fish River Formation, Walford Dolomite (or the Ptp_3 member of the Peters Creek Volcanics) and Mount Les

Siltstone. Sweet et al. (1981) suggested a possible paraconformity exists with the Mount Les Siltstone in the Hedleys Creek area, but mapped the contact as an unconformity west of Gorge Creek. Drillhole correlations by Rowley (1983) also supported the idea of an unconformity, at least locally.

Sweet et al. (1981) mapped the Doomadgee Formation as three informal members Ꝑfd$_{1-3}$ distinguished mainly by the presence of a black shale Ꝑfd$_2$ in the middle of the formation. In most outcrops the base of the Doomadgee Formation is a 1 - 2 m thick silicified pebble to boulder conglomerate with a poorly sorted sandstone matrix. Rowley (1983) reported that this conglomerate is more than 5 m thick 1.5 km northeast of Lead Hill. It appears finer grained in the east and near the Queensland/Northern Territory border. The basal conglomerate (Ꝑfd$_1$) is overlain by green to grey, fine to medium grained quartz sandstone with variable levels of silicification. Minor dolostone beds were mapped about 60 m above the base of the formation in the type section and have been intersected in several cored drillholes. Esso holes GCD-1, 2A and 4 intersected these beds of ferroan dolostone ranging from 16 m to 55 m thick (Rowley, 1983).

The middle section of the Doomadgee Formation (Ꝑfd$_2$) is readily discernible from Ꝑfd$_1$ on aerial photographs and occurs sporadically in outcrop in highly lateritised gullies. It is best observed in creek cuts. On Wire Creek there is a 7 m cliff of interbedded dark grey to black partly fissile, carbonaceous shale and siltstone with subordinate fine grained sandstone interbeds. The outcrop is both faulted and folded. This outcrop is overlain by a several metre thick oolitic bed that, although within the Pfd$_2$ area mapped by Sweet et al. (1981), was not recognised by them. Both the carbonaceous shales and the oolitic horizon were intersected in Amoco 83-4, although the oolite zone was only thinly developed (about 10 cm).

The base of the Pfd unit was described by Rowley (1983) as containing dolostone nodules and concretions with minor disseminated mineralisation. Sweet et al. (1981) estimated the unit to be 30 m thick at the type section near Gorge Creek. Aquitaine and Esso drillholes show thicknesses ranging from 45 to 51 m.

The upper part of the Doomadgee Formation (Pfd$_3$) contains the most variation in lithology and has a correspondingly variable topographic expression on aerial photographs. It ranges from plateaux and mesas east of Wire Creek to low lying areas of sparse outcrop near drillhole Esso GCD-1. The unit generally consists of variably silicified dolomitic sandstones at the base grading to laminated very fine grained sandstones interbedded with siltstones in the upper section (Plate 8, d). The basal section is more resistant and forms the area of highest relief. The sandstone is generally thin-bedded to laminated with common low-angle cross-beds, some of which show evidence of slumping. Pebble conglomerates and fissile micaceous shales are developed locally. Rowley (1983) reported stromatolites in the basal part of this member. Several shale units crop out as strike ridges between the drillholes Esso GCD-1 and Amoco 83-4. These units appear to be lenticular and at least two appear to merge to the northeast. Ripples and flute marks were also observed in outcrop along Wire Creek. The Ᵽfd$_3$ unit is believed to thin to the east, mainly because of the erosion associated with the deposition of the overlying South Nicholson Group sediments. This unit is known to reach about 400 m thick in the Northern Territory. Sweet et al. (1981) estimated a thickness of 180 m for the type section of Ᵽfd$_3$. To the east, Esso drillhole GCD-4 intersected about 90 m.

Ferruginous pisolitic laterites are commonly developed on the Doomadgee Formation (Plate 8, c).

Comalco's 1992 petroleum exploration drilling in the northern Mount Isa Basin intersected the Doomadgee Formation equivalent, the Lawn Hill Formation in Egilabria-1.

3.7.3 The Riversleigh Fold Zone and the southern Bowthorn Block

This section of the thesis outlines the results of a two week field trip undertaken by J.N. Dunster, J. Moultrie, A.D. Schaap and the author. Figure 3-8 shows the location of the Riversleigh Fold Zone. Field data have been combined with AGSO (formerly BMR) 1:100 000 scale mapping reported by Sweet and Hutton (1980) and drillhole logging of Amoco and DME Geological Survey of Queensland (GSQ section) cored drillholes to analyse this area. Thin section analysis of samples from these drillholes was undertaken by Moultrie (1991a) under this writer's supervision. Lithostratigraphic mineral drilling data from many shallow exploration bores was also available from this region (e.g. Johnston, 1975).

The stratigraphy detailed is the package of rocks called the Lawn Hill Platform, but more accurately it is divided into two groups, the lower and upper McNamara Groups. These rocks are placed stratigraphically above the unconformity at the top of the Kamarga Volcanics and Yeldham Granite and below the significant unconformity at the base of the Constance Sandstone that is the basal level of the South Nicholson Group (Figures 3-9 and 3-22). Plumb and Derrick (1975), introduced the term "Lawn Hill Platform" to describe the rocks of similar age, which are continuous with but less deformed than, the rocks of the Cloncurry Orogen. The results of the ATP 423P seismic work suggest that this is an inappropriate structural and stratigraphic term for this rock sequence as the word platform has depositional connotations that are misleading especially for an asymmetric sequence containing carbonates that are the only true platform sediments in the Mount Isa Basin. The McNamara Group of Sweet and Hutton (1980) divided into upper and lower packages, is used to describe the sequence reported in this part of the thesis.

Outcrop of the McNamara Group within ATP 423P is confined to the southeastern portion of the area where uplift and erosion has removed much of the post-Proterozoic cover (Plate 8, a). Many contacts between formations and members can be observed in the field. However, these are commonly faulted and brecciated or masked by surficial cover. In outcrop the contacts appear to interdigitate over distances of tens of metres in some cases and hundreds of metres in others, resulting in significant difficulty in recognising identified major seismic unconformities within the McNamara Group. Typical outcrop is shown in Plate 8, b.

Basal volcanic rocks

The oldest rocks exposed in outcrop in the region are the Kamarga Volcanics that are intruded by the Yeldham Granite. These volcanic rocks almost certainly correlate with the Peters Creek Volcanics of the Murphy Inlier on the basis of the lithostratigraphy and seismic stratigraphy observed within the Bowthorn Block. The basal volcanic sequence was not penetrated in the 1992 Comalco petroleum drilling because it was not believed to be prospective.

<u>Kamarga Volcanics (Ᵽas)</u>

The Kamarga Volcanics (Ᵽas on the AGSO Lawn Hill Region 1:100 000 sheet) are blocky to flaggy, medium to coarse, feldspathic, conglomeratic and ferruginous sandstones with minor siltstone, interbedded with vesicular, amygdaloidal and massive basalts. Flow top breccias are common and interbeds of feldspathic and conglomeratic sandstone also occur between the flows that are up to 40 m thick. Difficulty was experienced in distinguishing these sedimentary strata from the overlying Torpedo Creek Quartzite (Ᵽmp), but an angular unconformable relationship can be observed on aerial photographs. The composition of the clastic sandstone interbeds is quartzose sandstone to arkose. The stratigraphic thickness of the Kamarga Volcanics is estimated to be 1400 m. Brecciated flow tops and massive volcanic flows with vesicular flow tops suggest that the lavas were erupted subaerially or into a shallow water depositional environment.

Yeldham Granite (Ɫty)

The Yeldham Granite (Ɫty) is medium grained muscovite leucogranite with pegmatite dykes and minor greisen. Its contact with the Kamarga Volcanics is poorly exposed, but both a cross-cutting relation and poorly developed metamorphic aureole were observed by Sweet and Hutton (1980). The presence of graphite in several late stage phases of this intrusive rock probably indicates contamination of the granite by carbonaceous country rock.

Lower McNamara Group

Figures 3-9 and 3-25 illustrate the regional correlations and detailed stratigraphy of the McNamara Group. The various lithostratigraphic units intersected in the 1992 Comalco petroleum drilling are shown on Table 3-13.

Torpedo Creek Quartzite (Ꝑmp)

Sweet and Hutton (1980) described the Torpedo Creek Quartzite as massive to blocky medium grained sandstone that is conglomeratic in part, but particularly near the base. Malachite staining is common. The conglomerate is polymictic with granitic and volcanic clasts present. Grain size ranges from pebbles to cobbles. The formation contains no subdivisions and ranges from 0 to 100 m thick with exposures principally confined to the area of the Kamarga Dome. Dip slope pavements are present. The formation unconformably overlies both Kamarga Volcanics and the Yeldham Granite. Sweet and Hutton (1980) interpreted its environment of deposition as fluvial with the upper part of the formation probably the result of a marine transgression. The Torpedo Creek Quartzite was not observed in the field because its outcrop distribution is confined to the region of the Kamarga Dome where access is difficult.

Gunpowder Creek Formation (Ꝑmw)

This formation predominantly comprises sandstone and siltstone and has been subdivided by Sweet and Hutton (1980) into three members that are from the base:

Ꝑmw$_a$ -- (base) micaceous siltstone, pyritic carbonaceous shale, siltstone and sandstone.

Ꝑmw$_b$ -- ferruginous, arkosic sandstone with minor conglomerate, siltstone and stromatolitic dolostone. In GSQ Lawn Hill-3 Ꝑmw$_b$ is carbonaceous shale interbedded with minor sandstone.

Ꝑmw$_c$ -- (top) dolostone, dolomitic siltstone, oolitic dolostone, dolomitic sandstone, carbonaceous siltstone and fine sandstone.

The unit occurs in the vicinity of the Kamarga Dome. It is much affected by weathered producing recessive outcrop, and has a stratigraphic thickness of between 400 and 800 m. The environment of deposition of this unit is interpreted to be fluvial to lagoonal and shallow marine.

Paradise Creek Formation (Ꝑmx)

The base of the Paradise Creek Formation is the Mount Oxide Chert Member, Ꝑmo. This crops out at Lawn Hill although it is poorly developed. It comprises grey laminated chert. It was not observed in the drillholes GSQ Lawn Hill-3 or -4 that both penetrated this part of the stratigraphy. In these drillholes the upper boundary of the Gunpowder Creek Formation is marked by a change from laminated dolostone and silty dolostone to graded siltstones and carbonaceous shales.

The Paradise Creek Formation comprises laminated and stromatolitic dolostone, dolomitic siltstone and sandstone and minor chert. A breccia that may be

Paradise Creek Formation or possibly Lady Loretta Formation was observed in the section through the Ploughed Mountain Anticline (Plate 9, b). This breccia contains angular clasts up to 30 cm across embedded in a fine grained carbonate matrix. The Paradise Creek Formation was observed in GSQ Lawn Hill-3 and -4 and consists predominantly of fine grained laminated carbonate. In outcrop, cauliflower cherts and limonite after gypsum are common with minor oolite layers. Outcrop of the Paradise Creek Formation is mostly confined to the area around the Kamarga Dome, however, further north the formation also is exposed in the core of the Ploughed Mountain Anticline. The environments of deposition are interpreted to be fluvial, lagoonal and shallow marine.

Esperanza Formation (Pmz)

The Esperanza Formation overlies the Paradise Creek Formation. It comprises stromatolitic chert, siltstone, sandstone and dolostone. In the field, laminated chert and siliceous columnar stromatolites interspersed with breccia were observed southwest of the Kamarga Dome. The breccia appeared to be both tectonic and intraformational. Ferruginous sandstones and siltstones that comprise the upper portion of the sequence were observed in the field. The formation has a stratigraphic thickness of 200 to 250 m, and outcrops are widespread in the Lawn Hill region including the Ploughed Mountain Anticline. The environment of deposition is thought to be generally shallow marine. River channels and restricted beaches plus some still water settings also appear to be present to account for the clastic rocks within the unit.

Lady Loretta Formation (Ꝑml)

This formation is thinly bedded to laminated intraclastic and stromatolitic dolostone with interbeds of dolomitic siltstone and fine sandstone. A basal unit, Ꝑml$_b$, comprising chert breccia and altered siltstone cemented by limonite, was reported by Sweet and Hutton (1980) and a top unit, Ꝑml$_t$, comprising basal blocky orthoquartzite, overlain by flaggy fine sandstone siltstone and dolostone, is present in the type section. The formation comprises some 2000 m of stratigraphic thickness with the upper portion being the section observed in the field.

The type section of the Lady Loretta Formation contains abundant stromatolites (Plate 3, a and b) that could be broadly subdivided into columnar, hemispherical or pustular types with interspersed clastic beds increasing towards the contact at the top of the formation. Algal textures are common throughout, and cyclic sedimentation on a small scale appears to have occurred resulting in distinctly benched outcrop. The sandstone interbeds contain low angle cross-beds with ripple cross-laminae and small scale ripple structures. Both symmetrical and asymmetrical ripples were observed and platy breccias are present, though not common. Bidirectional ripples were observed at one location. The Lady Loretta Formation crops out as low rolling hills. The upper boundary is considered the base of the first orthoquartzite bed. However, a gradational contact was observed in the field with a brecciated zone at the contact itself.

A study of drillhole Amoco 83-5 showed that the formation is commonly pyritic and carbonaceous with slump structures in the siltstone beds. Sweet and Hutton (1980) observed edgewise or sharpstone conglomerate in places. Throughout the widespread outcrop, ripple marks, cross-beds, intraclast dolostone layers, oolites, clay balls and mud cracks have also been reported. The formation is interpreted to be a tidal to deep marine shelf and slope bypass margin deposit. This environment is characterised by periodic subaerial exposure with the development of oolite and stromatolitic banks probably forming next to a stable land mass.

Comalco drillholes Desert Creek-1 and Argyle Creek-1 both intersected the upper part of the Lady Loretta Formation. In each case this formation comprised dolomitic limestone with minor fine grained clastic interbeds. Although the formation was tight in both wells with velocities over 7000 ms^{-1}, the oolitic packstone and grainstone textures in Desert Creek-1 suggest that very early porosity and permeability were present. Trace lead, zinc and copper sulphide mineralisation observed in this unit in Argyle Creek-1 also indicates that metal-rich fluids migrated through the formation.

Upper McNamara Group

Shady Bore Quartzite (Pms)

The Shady Bore Quartzite comprises white flaggy to massive medium orthoquartzite with fine sandstone siltstone and dolostone interbeds. This formation was observed in several localities in the field where it was found fine to medium grained clean siliceous quartzose sandstone that appears to unconformably overlie the Lady Loretta Formation (Plate 10, a).

Sweet and Hutton (1980) described the Shady Bore Quartzite as dominated by sandstone in only a few localities. They reported recessive weathering of beds and scree covered slopes, with perhaps only 30% of the section exposed. The exposed beds comprise finer more friable sandstone, siltstone and dolostone. The sandstone dominates the outcrop, and this feature, along with its indurated nature, caused the unit to be described as a quartzite. The same situation applies to the northern basin margin where oil shows are present in similar highly silicified, quartzose sandstones.

The Shady Bore Quartzite is widely distributed throughout the Lawn Hill region and is present in both the Ploughed Mountain and Mount Caroline Anticlines north of Lawn Hill Station. Its stratigraphic thickness ranges from 70 to 590 m. Abundant sedimentary structures are present. These comprise ripple marks at the bases and tops of massive beds, mud flake conglomerates, mud layers draped over ripple marks, mud cracks, flute molds and halite casts (Plate 9, a). Laminated intraclastic and oolitic dolostones are present in the Ploughed Mountain Anticline while in the Mount Caroline Anticline the whole section is sandstone. In the orthoquartzite sections studied in the field, intraformational mudstones are sporadic and possible crystal growth structures (Plate 10, b) were observed at some levels. The deposition of the Shady Bore Quartzite was considered a shoreline lagoonal to peritidal environment by Sweet and Hutton (1980), however the sections inspected in the field clearly relate to beach deposits.

No equivalent of the Shady Bore Quartzite was observed in any of the ATP 423P drilling.

Riversleigh Siltstone (Ᵽmr)

The Riversleigh Siltstone comprises laminated and thin bedded, fine to coarse quartz siltstone and shale (Plate 8, a and b). Dolomitic and carbonaceous layers are common with thin sandstone interbeds. Several thin members were recognised in the field by Sweet and Hutton (1980). From the base they are as follows:

Ᵽmr$_{s1}$ -- (base) flaggy to blocky fine clayey sandstone with siltstone interbeds. This unit contains altered ferruginous, manganiferous dolostone and in the field we observed several similar interbeds in other locations.

Ꝑmr$_{s2}$ -- a thick bedded silicified fine to medium dolomitic sandstone with siltstone interbeds. The fresh rock is grey to black and strongly carbonaceous. Outcrops are mostly leached and white.

Ꝑmr$_{1}$ -- laminated quartz siltstone.

Ꝑmr$_{s3}$ -- light grey thin to thick bedded, medium to coarse quartz sandstone with clayey matrix.

Ꝑmr$_{w}$ -- (top) white leached clayey siltstone and shale and this is the highest unit recognised below the Termite Range Formation.

The Riversleigh Siltstone is widely distributed throughout the area and has a stratigraphic thickness of 570 - 3200 m. The formation thins northward from the type section where it is some 3200 m of stratigraphic thickness, to the Mount Caroline Anticline where some 800 m is present. This is consistent with the thinning observed on the seismic sections through the Bowthorn block further north. In the Kamarga Dome 570 m of stratigraphic thickness is present. Many sedimentary structures exist, but most of these appear to relate to deep water deposition. In drill core in Amoco 83-1 syndepositional slumping appears to have been very common with many units exhibiting graded beds consistent with turbidite deposits.

In outcrop, the formation exhibits subdued relief due to differential erosion, with thin sandstone and dolomitic interbeds. Sedimentary structures include wavy and lenticular beds, pinch and swell structures, possible hummocky cross-stratification and internally ripple laminated beds with flute casts. Sweet and Hutton (1980) reported mud cracks in places, however none were observed in the field sections during the current work. Some possible synaeresis features (derived from dewatering due to load) were observed. The Riversleigh Siltstone is interpreted to have formed during a period of general basin subsidence from a shallow water high energy environment to a deeper water low energy setting. The unit lacks shallow water current structures and is highly carbonaceous possibly indicative of vertically accreted distal turbidite deposition in a deep water marine environment.

Much of the stratigraphic section of Riversleigh Siltstone was intersected in Comalco drillholes Desert Creek-1 and Argyle Creek-1. In each hole the formation comprises massive siltstone that is commonly carbonaceous and contains rare dolomitic limestone interbeds near the base. In both drillhole locations, but particularly at Argyle Creek-1, the basal part of the Riversleigh Siltstone was probably not present due to northward lapout from the deep basin in the direction of the Murphy Inlier.

Termite Range Formation (Ᵽmt)

The Termite Range Formation comprises interbedded sandstone quartzwacke, greywacke, siltstone and shale (Plate 10, c). Several members within the formation have been recognised. From the base they are:

Ᵽmt$_1$ -- (base) thick bedded poorly sorted sandstone and quartzwacke interbedded with siltstone.

Ᵽmt$_2$ -- thin to medium bedded light brown clayey siltstone and ferruginous fine to medium sandstone.

Ᵽmt$_{3g}$ -- dark grey medium to thick bedded silicified quartzwacke interbedded with laminated siltstone and shale.

Ᵽmt$_3$ -- (top) white to light brown and grey thick bedded fine to coarse poorly sorted sandstone and lithic greywacke interbedded with laminated siltstone.

The Termite Range Formation is 200 to 1100 m thick and widely distributed in the Lawn Hill region. Drillholes Amoco 83-1 and 83-2 contain abundant slump structures and graded cyclic bedding. The formation occurs in outcrop in the Lawn Hill region as prominent treeless strike ridges with sporadic termite mounds (therefore the name Termite Range). It thins to the east and south.

The formation features regular alternation and continuity of thickness of siltstone and sandstone beds plus rare sedimentary structures that include parallel laminations, mud clasts, ripple laminations and graded beds. It is distinguished from the overlying formation by a change from massive sandstone to carbonaceous shale that weathers easily and forms the low relief units of the Lawn Hill Formation. Pinch and swell structures were observed in the field in the interlaminated and interbedded sandstone units. The environment of deposition of this formation is interpreted to be deep water, possibly a turbidite setting. This is based on the lack of sedimentary structures apart from graded beds and sole marks. Nothing observed in the field is at variance with this interpretation first postulated by Sweet and Hutton (1980).

In the 1992 Comalco petroleum drilling, the Termite Range Formation was intersected in both the Desert Creek-1 and Argyle Creek-1 drillholes. In each case the formation comprised mostly carbonaceous siltstone with rare lithic to quartzose sandstone interbeds up to 50 m thick. The thick sandstone beds are interpreted as submarine channel sandstones.

Lawn Hill Formation (Ɽmh)

The Lawn Hill Formation comprises siltstone, shales, tuff, minor sandstone and dolostone. It is divided into six units that are widely recognised and well defined particularly at Century. The Century deposit is contained within unit Ɽmh_4. From the base they are:

Ꝑmh$_1$ -- (base) grey to black carbonaceous shale, flaggy siltstone and grey silty concretions. Minor tuff is also present.

Ꝑmh$_2$ -- greyish green fissile to flaggy tuff and tuffaceous siltstone with thinly interbedded siltstone, sandstone and shale.

Ꝑmh$_3$ -- flaggy to blocky micaceous lithic sandstone and conglomeratic sandstone with shale clasts commonly present at the base.

Ꝑmh$_4$ -- grey fissile to flaggy siltstone and shale. It contains tuffaceous siltstone and sandstone with flaggy tuff interbeds and minor dolostone in the upper part of the unit.

Ꝑmh$_5$ -- reddish brown, flaggy to blocky, fine to medium, ferruginous, micaceous, feldspathic sandstone with brown to purple siltstone interbeds.

Ꝑmh$_6$ -- (top) brown and green shale and flaggy thin bedded siltstone and fine sandstone. In the type section south of Century this unit unconformably underlies shallow dipping Constance Sandstone with a prominent angular relationship.

The Lawn Hill Formation is widely distributed and individual members have been recognised throughout the 1:100 000 scale AGSO Lawn Hill Region mapped area. The certainty with which these correlations have been made, based on aerial photography and lithologic descriptions, is somewhat dubious as many units are present in outcrop as short deformed isolated strike ridges projecting through the black soil plains in the Lawn Hill region (Plate 10, d). The basal unit, Pmh$_1$, exhibits convolute bedding and contains ovoid concretions. The black carbonaceous shales of this unit were reported to contain volatile hydrocarbons based on analyses by R.L. Jack and reported in Ball (1911). This unit was probably deposited in relatively quiescent deep water conditions. Pmh$_2$ contains devitrified (silicified) glass shards, tuffs and vesicles infilled with zeolites in places. In the type section, rare conglomerates and quartzose sandstone cross-beds with chert clasts and intraformational clasts were observed. This unit appears to represent the onset of shallowing upward conditions. Pmh$_3$ forms massive resistant ridges and it appears to lens out in the syncline between Ploughed Mountain and Mount Caroline Anticlines. In the type section this unit is sandy and cross-bedded, but rapidly grades up to the fine grained, overlying unit Pmh$_4$. Pmh$_4$ contains the Century deposit and is tuffaceous in part. At Century the unit is fine grained and dolomitic with sphalerite and galena present as abundant fine laminae and layers. The base of the unit comprises black carbonaceous mudstones. Overlying the Pmh$_4$ unit is Pmh$_5$ that at the base is dolomitic and thus forms prominent strike ridges in contrast to the recessive Pmh$_4$. Pmh$_5$ contains cross-beds, ripple marks and mud flake conglomerates and is possibly glauconitic in part. Mud cracks were observed in the field within this unit indicating exposure and possibly a tidal channel environment of deposition. Pmh$_6$ crops out in only a few places. It is well exposed in the type section to the south of Century where it is laminated and fine grained with few sedimentary structures suggesting a quiet water deposition setting.

The Lawn Hill Formation was fully intersected in Egilabria-1 during the 1992 Comalco drilling program. The lower part of the formation was also penetrated in Beamesbrook-1. In Egilabria-1 the Lawn Hill Formation is interpreted to be transitional between the deeper water Termite Range Formation and the shallow water South Nicholson Group. The unit appears similar in lithology to that described from outcrop, but contains more carbonate in drillhole Egilabria-1.

Other units

Several units within this part of the northern Mount Isa Basin were not studied due to lack of time, however they are described in Hutton and Sweet (1982), Blake (1987), Sweet (1983, 1984, 1985) and elsewhere. These units comprise the Carrara Range Group in the southwest of the basin, and the lower units in the Mount Oxide Region stratigraphically between the Eastern Creek Volcanics and the Surprise Creek Formation.

Where the Surprise Creek Formation and the Fiery Creek volcanics were inspected at one location to the north of the Fiery Creek Dome, each appeared to contain significant thicknesses of coarse clastic deposits (Plate 9, c and d).

3.7.4 The upper section of the northern Mount Isa Basin

South Nicholson Group

The South Nicholson Group is present within both the Bowthorn Block and the Riversleigh fold zone.

The existing strata of the northern Mount Isa Basin were faulted, folded and partly eroded before the deposition of the overlying sediments of the South Nicholson Group. This structuring was probably related to thrusting that created the highland provenance area that sourced the South Nicholson sequence. The thrust zones appear to have been confined to the southern flank of the basin.

The South Nicholson Group consists of the Constance Sandstone, Mullera Formation and the Tidna (Mittiebah) Sandstone. The formations are best exposed in the Riversleigh Fold Zone, but also occur throughout the Bowthorn Block. The lithologies and stratigraphy are illustrated in Figure 3-26 after Sweet and Slater (1975), and Carter and Zimmerman (1960).

<u>Constance Sandstone (Psa)</u>

The Constance Sandstone is mapped as unconformably overlying the Doomadgee Formation between Hedleys Creek in the east and the Northern

Territory border in the west (AGSO map, Sweet et al., 1981). The Constance Sandstone was probably inadvertently mapped overlying the Doomadgee Formation with a conformable relationship north of Connolly (Burangoo) Waterhole on the Nicholson River. This conformable interpretation is presumed to be a drafting error although it may relate to the lack of basal conglomerate in that area. The extent of the disconformable relationship between the Lawn Hill Platform and the South Nicholson Group is obvious on satellite imagery of the Lawn Hill area and in outcrop in the Northern Territory. Here the Constance Sandstone overlies all the units of the Fickling Group and represents the erosion of up to several hundred metres of section. This demonstrates significant structuring within the Lawn Hill Platform sequence before the deposition of the South Nicholson Group. On the northern margin of the basin however, a disconformable (possibly paraconformable) relationship is present (Plate 11, c). Seismic lines 89BN-06 and 89BN-07 suggest a conformable contact.

At Century and elsewhere some 30 to 300 m of erosion is present at the top of the McNamara Group below the unconformity at the base of the South Nicholson Group.

The Constance Sandstone is dominantly medium grained quartz sandstone. Sweet and Slater (1975) mapped three lenticular siltstone bodies as members of the formation, and speculated that the uppermost member could represent part of the overlying Mullera Formation.

The basal Constance Sandstone (Ᵽsa_1) is well exposed in and around Gorge Creek and near Wire Creek. In both locations it is a pebble to boulder conglomerate containing well rounded clasts of quartzite and stromatolitic chert. Even at a close scale, where the basal Constance Sandstone unconformity is exposed, it appears to be conformable with the underlying Doomadgee Formation (Plate 11, a) unlike in the Riversleigh Fold Zone where the unconformity is highly angular at all scales from Landsat to local outcrop (Plate 4, b). The unconformity is overlain by a sequence of intensely cross-bedded medium to coarse sandstones with sporadic pebble conglomerate layers (Plate 11, d). Most outcrops are now almost entirely silicified as indeed was the unit in the subsurface, based on the 1992 Comalco petroleum drilling. The sandstones thin to the west from 130 m at Hedleys Creek to 80 m at Gorge Creek and are virtually absent near Fish River.

Because of the thinning of Ᵽsa_1 to the west, the contact with the overlying Pandanus Siltstone Member (Ᵽsa_p) occurs progressively nearer to the base of the Constance Sandstone in the west. In outcrop, the Pandanus Siltstone Member consists of fissile to flaggy green purple and brown micaceous siltstone and thin sandstone interbeds. It contains more sandstone in the Northern Territory and thins away from a maximum of 130 m in the Gorge Creek area to about 50 m near Wire Creek and may lens out entirely east of Hedleys Creek. The siltstone weathers easily and usually only crops out where it is capped by silicified sandstone. Its upper section at least can be mapped in Wire Creek although its lower contact with Psa_1 is obscured by alluvium.

The Pandanus Siltstone Member is overlain by strongly silicified medium to coarse quartz sandstone (Ꝑsa$_2$) that forms rugged dissected plateaux and cuestas. In outcrop it is progressively more silicified and more prominently jointed up section. Cliffs along Wire Creek provide spectacular exposures of the upper part of the unit and the lower part is well exposed south of Connolly (Burangoo) Waterhole on the Nicholson River. Cross-bedding is moderately common especially near the middle of the unit and ripple marks are rare. Thin lenticular interbeds of granule and pebble conglomerate occur sporadically throughout Ꝑsa$_2$. Sweet et al. (1981) estimated that this unit reached a maximum of about 320 m thick 3 km west of Fish River, from where it thins progressively eastwards. Aerial photograph interpretations suggest that at least 180 m is present at Hedleys Creek.

The Wallis Siltstone Member (Ꝑsa$_w$) is virtually identical with the Pandanus Siltstone Member in outcrop pattern and lithology. Sweet et al. (1981) also reported thin glauconitic sandstone within the Wallis Siltstone. It is well exposed near the junction of Wire Creek and the Nicholson River. In the Hedleys Creek to Fish River area, the Wallis Siltstone Member forms two distinct lenses. Sweet et al. (1981) assumed these to be separate tongues of a member continuous in the subsurface to the south. Near the Nicholson River the Wallis Siltstone is between 90 and 100 m thick.

The Wallis Siltstone is overlain by a distinctive reddish brown, cross-bedded medium and coarse quartz sandstone with a sparse clayey matrix (Ꝑsa$_3$). It is well exposed south the junction of Wire Creek and the Nicholson River where it forms relatively flat areas of outcrop and float. Silicification, and cementation by iron-rich solutions are patchy and the sandstone outcrop ranges from friable to highly silicified. Aerial photographs show that it is relatively free of large scale obvious jointing. Ꝑsa$_3$ thins to the west, from 100 to 160 m ten kilometres south of Hedleys Creek, to 96 m in the Northern Territory.

The uppermost siltstone member of the Constance Sandstone mapped by the AGSO is the Bowthorn Siltstone Member (Ꝑsa$_b$). Sweet et al. (1981) suggested that Ꝑsa$_4$ lenses out westwards, and that the Bowthorn Siltstone Member is a tongue of the Mullera Formation. It is unimportant whether Ꝑsa$_6$ represents a siltstone member of the Constance Sandstone or if Psa$_4$ is a sandstone within the Mullera Formation, but their close relationship strongly suggests that the Constance Sandstone and Mullera Formation interdigitate at least on the northern flanks of the basin.

Carter and Zimmerman (1960) reported that in the Lawn Hill area the Constance Sandstone consists mainly of white, light brown and red, medium-fine to coarse-grained quartz sandstones. Beds are massive to flaggy. Surface silicification has produced "quartzite" sandstone over wide areas, but some exposed beds are friable. Some conglomeratic beds and lenses occur throughout the formation, and a lens of siltstone, similar to that in the Mullera Formation, and probably a few hundred feet thick, crops out north of Elizabeth Creek.

In addition, a succession of thin-bedded calcareous greywacke, quartz greywacke and quartz sandstone is exposed at the base of the formation in the scarp east of "Iron Deposit E" of Carter and Zimmerman (1960). Precipitation of iron oxide forming liesegang "roll front" lines perpendicular to bedding planes in the Constance Sandstone, is present at Lawn Hill Gorge National Park (Plate 4, d). The calcareous greywacke contains many spherical concretions, up to 250 mm in diameter. The succession is included in the Constance Sandstone, but with further mapping it should be delineated as a separate unit as it differs lithologically from the bulk of the Constance Sandstone.

The lower part of the Constance Sandstone is red, coarse-grained, conglomeratic, and friable; it is well-exposed in the Constance Range scarp. The upper beds are light brown and medium-fine to medium-grained; they are clearly bedded and are better sorted than the lower beds. White to light grey, highly siliceous, poorly bedded strata are seen only on elevated flat surfaces. Their appearance is the result of supergene silicification, probably related to lateritisation.

Cross-bedding of various types, and ripple marks, are common throughout the Constance Sandstone. Mud cracks were also commonly observed (Plate 11, b).

Comalco's 1992 petroleum exploration drilling in the northern Mount Isa Basin intersected the Constance Sandstone in both Argyle Creek-1 and Egilabria-1. Beamesbrook-1, drilled in 1988, is believed to have intersected a thin section of possible South Nicholson Group immediately below the Carpentaria Basin. The lithologies were similar in each well, with quartzose Constance Sandstone being interbedded with thick, occasionally red, siltstone units. Additionally, the Constance Sandstone in Argyle Creek-1 was highly glauconitic over several intervals. Rare thin limestone interbeds were observed in Egilabria-1. A fault contact is believed to be present between the upper McNamara Formation and the South Nicholson Group in Argyle Creek-1. The fault interpretation is based on the lack of coherent seismic reflections at that level in the well, the presence of calcite veining near the contact and the abrupt lithology change. A gradational contact was observed in Egilabria-1 where similar sandstone and limestone lithologies were present both above and below the seismic conformity at the base of the South Nicholson Group.

The lithological transition at the Constance Sandstone – Mullera Formation contact is abrupt in outcrop.

Mullera Formation (Psl)

The Mullera Formation forms only sporadic outcrops north of Elizabeth Creek, but crops out extensively in the Northern Territory and Lawn Hill areas. Carter and Zimmerman (1960) reported a stratigraphic thickness of 2000 m in the Lawn Hill area. They divided the formation into five informal units as shown in Table 3-8.

Siltstone –immediately below the Tidna Sandstone (Upper part of the Mullera Formation)
Middle Creek Sandstone Member
Siltstone (Middle part of the formation)
Train Range Ironstone Member
Siltstone (Lower part of the formation)

Table 3-8. Informal units of the Mullera Formation defined by Carter and Zimmerman (1960)

Only the Train Range Ironstone and the Middle Creek Sandstone members are reliable stratigraphic units, as the three siltstone successions are generally distinguishable only by superposition, not by lithology.

The dominant lithology is thin-bedded, commonly micaceous, siltstone, siliceous siltstone, shale and fine-grained sandstone. At some stratigraphic levels fine to medium-grained quartzose sandstone forms the main part of the succession, but these sandstone beds do not persist throughout the area of outcrop of the formation. The thickest and most persistent sandstone sequence is designated the Middle Creek Sandstone Member (see below). From 300 to 700 m above the base of the formation a zone rich in sedimentary iron begins. It consists of quartzose sandstone, siltstone, shale, oolitic ironstone and chamositic sandstone. It was defined as the Train Range Ironstone Member. Other thin ironstone beds and lenses (generally less than 15 cm thick) occur throughout the formation.

Shallow water sedimentary structures abound throughout the unit; they include ripple-marks, cross-bedding, scour and fill features, mud pellet casts, intraformational breccia, mud cracks, and possible rain prints. Small scale slumping has also been recorded. Well developed cone in cone structures occur in the upper Elizabeth Creek area (latitude 18°18'15"S, longitude 138°06'55"E).

Although the upper, middle and lower siltstone successions are generally not readily distinguishable by lithology, the lowermost 160 m of the formation contains more, and thicker, fine sandstone beds than is generally the case higher in the succession; dolomitic shale, some with cherty lenses and concretions, occurs in the lower siltstone in the upper Elizabeth Creek area, just below the ironstone member.

Tidna Sandstone (Mittiebah Sandstone, Ṗst)

Conformably overlying the Mullera Formation is the Tidna Sandstone (Mittiebah Sandstone in the Northern Territory). In the Lawn Hill area this reaches a maximum thickness of 400 m according to Carter and Zimmerman (1960). Ahmed and Wygralak (1989) reported a maximum thickness of 2700 m in the Calvert Hills area of the Northern Territory leading to some doubt about the reliability of the correlation.

In the Lawn Hill area Carter and Zimmerman (1960) reported that the Tidna Sandstone comprises medium to fine-grained quartzose sandstone, with some interbedded siltstone and shale. In the southern syncline (Southern Basin of Carter and Zimmerman, 1960) the base of the succession is marked by a massive, white to light brown, medium to coarse-grained, quartzose sandstone, but in the northern syncline the passage from Mullera Formation to Tidna Sandstone is transitional. The base of the formation in the northern syncline is placed at the point where a predominantly arenaceous succession of thinly flaggy sandstone occurs. It is about 20 to 50 m above the uppermost thin ironstone bed. A thin ferruginous sandstone has been recorded in the southern syncline but not in the northern syncline.

3.7.5 Outcrop distribution and depositional environments

The complete stratigraphic thickness of the McNamara Group ranges from about 11 km in the southern Lawn Hill region to about 8 km near Ploughed Mountain and Mount Caroline Anticlines. Some of this thinning may relate to penecontemporaneous development of the anticlines as the stratigraphic thickness on the southern end of the Comalco seismic line 90BN-25 at Elizabeth Creek is about 10 km.

Name of formation	Thickness (m)	Predominant lithologies	Environments of deposition
Lawn Hill Formation	1800-2200+	Shale, siltstone, tuff, tuffaceous siltstone, sandstone, dolostone	Deep water sedimentation, low current activity, euxinic conditions, volcanicity. Widdallion Sandstone Member (Figure 3-25) may represent a higher energy environment in relatively shallow water, possibly a marine shelf. Deep water at the base evolving upward to shallow emergent tidal and fluvial setting
Termite Range Formation	200-1100	Feldspathic and lithic sandstone, quartzwacke, greywacke, siltstone, dolostone	Lack of sedimentary structures except graded beds and sole marks suggests a deep water turbidite (contourite) environment. Partial Bouma sequences recognised
Riversleigh Siltstone	970-3200	Quartzose, dolomitic and carbonaceous siltstone; shale, dolomitic sandstone, dolostone	Period of general basin subsidence from a shallow water high energy environment to a deeper water low energy situation. Unit lacks shallow water current structures. Carbonaceous units are possibly deep water euxinic deposits
Shady Bore Quartzite	70-590	Orthoquartzite, siltstone, dolostone, fine sandstone	Shoreline, lagoonal, peritidal environments, beach deposits in places
Lady Loretta Formation	2000	Laminated, stromatolitic and intraclastic dolostone; dolomitic siltstone and sandstone; basal ferruginous breccia	Extensive marine shelf, characterised by periodic subaerial exposure and crossed by oolite and stromatolite banks, next to a stable mature landmass, i.e. tidal to deep marine shelf and slope margin
Esperanza Formation	200-250	Stromatolitic chert; siltstone, sandstone and dolostone	River channels or restricted beaches in a shallow marine environment. Deeper water than units occurring above and below
Paradise Creek Formation	500	Dolostone, stromatolitic dolostone; minor siltstone sandstone and chert	Flat stable shallow water shelf with local basins, some evaporitic, possibly formed by ooid banks. Shallow to emergent marine environment
Gunpowder Creek Formation	400-800	Carbonaceous shale, siltstone, ferruginous feldspathic sandstone, dolostone, dolomitic sandstone	Fluvial, shallow marine and lagoonal deposits at the margin of a landmass
Torpedo Creek Formation	0-100	Conglomerate, feldspathic and quartzose sandstone; minor siltstone and shale	Fluvial deposits at the base and probably the product of a marine transgression at the top
Kamarga Volcanics	1400	Amygdaloidal and massive basalt; feldspathic, ferruginous and conglomeratic sandstones	Brecciated flow tops and massive volcanic flows with vesicular flow tops suggest that the volcanics were erupted subaerially or into shallow water

Table 3-9. Interpreted environments of deposition within the McNamara Group and underlying volcanic rocks (after Sweet and Hutton, 1980)

Name of formation	Thickness (m)	Predominant lithologies	Environments of deposition
Tidna Sandstone (Mittebah Sandstone)	0-300+ (?2700)	Quartzose sandstone	Probably fluvial to shallow marine
Mullera Formation	0-1800+	Siltstone, shale, sandstone and oolitic ironstone	Lacustrine (lagoonal) to shallow marine
Bowthorn Siltstone	300-1000 (Includes Pandanus, Bowthorn and Wallis Siltstones)	Siltstone	Fluvio-deltaic to shallow marine overbank deposits
Wallis Siltstone		Siltstone	Fluvio-deltaic to shallow marine overbank deposits
Pandanus Siltstone		Siltstone	Fluvio-deltaic to shallow marine overbank deposits
Constance Sandstone		Quartzose sandstone, minor siltstone and conglomerate	Emergent fluvial to shallow marine conditions (possible laterisation)
Doomadgee Formation	180-490	Carbonaceous mudstone, siltstone and lithic sandstone with minor dolostone	Fluctuating depositional environments ranging from high energy fluvial to shallow marine near the base to deep water shales and finally shallow clastic sediments and dolostones
Mount Les Siltstone	55-90	Dolomitic siltstone and carbonaceous shale	Shallow marine to emergent fluvial conditions. Probable unconformity at the base of this unit
Walford Dolomite	260-420+	Oolitic, stromatolitic and intraclastic dolostone with minor dolomitic sandstone and shale, evaporites	Shallow, warm, intertidal to subtidal marine conditions with sporadic supratidal (sabkha type) environments
Fish River Formation	10-250	Orthoquartzite with interbedded siltstone	Emergent fluvial conditions
Peters Creek Volcanics	1500-2000	Rhyolite, tuff and basalt with intercalated dolostone, siltstone and lithic sandstone	Subaerial, fluvial and shallow marine conditions
Wire Creek Sandstone	0-70	Pebbly sandstone and conglomerate	High energy fluvial channels and braid plains

Table 3-10. Interpreted environments of deposition within the South Nicholson and Fickling Groups and underlying clastic and volcanic rocks (after Carter and Zimmerman, 1960; Sweet and Slater, 1975; Ahmad and Wygralak, 1989)

The main thickness variation in the Lawn Hill region is due to the thinning of the Riversleigh Siltstone from 3200 m in the type section in the south to 800 m in the Mount Caroline Anticline. As other formations maintain a relatively constant thickness, the timing of structuring in the Ploughed Mountain and Mount Caroline Anticlines may correspond to the deposition of the Riversleigh Siltstone.

Based on the AGSO 1:100 000 scale geological maps (Sweet et al., 1981; Hutton and Wilson, 1984; Wilson and Grimes, 1984) it is possible to infer that additional sedimentary formations and thickening of the basin occurs in a south-easterly direction creating a very large wedge shaped profile. The additional units include the Surprise Creek Group and the Fiery Creek Volcanics. Figure 3-6 shows the additional groups in relation to those in the southern Mount Isa Basin.

The outcrop distribution modified from the "cover sequences" of Blake (1987) and derived from the detailed mapping are presented in Figure 3-27. These show the basement and basin sedimentary sequence distribution throughout the region.

Tables 3-9 and 3-10 show the interpreted depositional environments throughout the McNamara, Fickling and South Nicholson Groups and the basal volcanics. Many conditions prevailed throughout the basin evolution and these were largely the result of the basin forming processes and the palaeoclimate. The difficulties of interpreting depositional environments in deep water Proterozoic rock sequences are acute. Despite this, there appears to be a basin evolutionary pattern in the northern Mount Isa Basin indicative of the main processes during the basin's history.

Long (1978) described the interpretation difficulties with Proterozoic fluvial deposits. The two particularly contentious areas of interpretation in the northern Mount Isa Basin are the deep water environment at the bases of the upper McNamara and Fickling Groups and the fluvial interpretation for much of the South Nicholson Group. In each case, there is as much clear evidence as could reasonably be expected in sequences lacking terrestrial vegetation and containing very few environmentally controlled organic remains.

Because the McNamara and Fickling Groups are equivalent formations and the McNamara Group is the thickest and contains the most detail, it is proposed to use this nomenclature for the deep basin stratigraphy.

By comparison, interpreted depositional environments in the McArthur Basin are predominantly shallow water facies in both the passive margin sequence (Muir, 1979; Muir, 1983) as expected, but also the foreland basin phase (Donnelly and Crick, 1988; Powell, et al., 1987; Plumb and Roberts, 1992). The later environments suggest a classic eu- versus miogeosynclinal relationship between the Mount Isa and McArthur Basins. In modern terms, an epicratonic foreland versus intracratonic sag setting.

The relationship between the McNamara and Fickling Groups (both upper and lower) can be interpreted from the ATP 423P drilling and seismic data (Figure 3-22). The results showed that McNamara Group nomenclature from the exposed outcrop in the Riversleigh Fold Zone was the most appropriate for the deeper part of the Bowthorn Block, but obviously two groups based on the passive margin phase carbonates and foreland clastics will be necessary in future.

3.8 SEISMIC ANALYSIS

Seismic source and receiver parameters are very important to achieve the best quality data for processing. Relatively long source receiver offsets were used in the northern Mount Isa Basin to image the deeper data.

Some lines were processed on a Micromax computer system in the field (an example is presented in Figure 3-28) and this work enabled fine tuning of the processing parameters (Appendix 1) particularly the velocity scans. The seismic accession and processing parameters for the 1991 survey are presented in Table 3-11. This was the final survey in ATP 423P and by that stage the parameters were best tuned to the acoustic properties of the northern Mount Isa Basin rock sequence.

Seismic acquisition and processing of ATP 423P seismic data were relatively straight forward (McQuillin et al., 1984 provided a general description of the technique) as most work was undertaken within the Bowthorn Block. The various detailed technical data and contour interpretations (using the techniques of Tearpock and Bischke, 1991) were reported in Meaney et al. (1991a; 1991b and 1992). Beyond the southern limit of this block, more sophisticated techniques such as those used by Brown and Everette (1991) to explore the Ouachita thrust zone through seismic windows would be necessary. Shallow tuned data designed to explore the overlying Carpentaria Basin did not produce clear images of the Proterozoic sequence in the Boomarra area of the southern Mount Isa Basin (e.g. McConachie, 1987b).

SOURCE	Energy Source: 3 x Failing Y1100 BBV vibrators Source Effort: 4 standing sweeps Sweep Range: 10 - 110 Mz, linear increment Sweep Length: 8.0 seconds linear upsweep Listen Time: 4.0 seconds Source Array: 3 Vibrators in line, 24 m (12 m pad to pad)
RECEIVER	Geophone: Sensor SM-4 10 Hz Number of Elements in Array: 12 Receiver Array: 37.5 m, linear, centred on station Group Interval: 25 m Station Interval: 50 m Fold: 30 m Number of Data Channels: 120 Spread Geometry: split asymmetric spread 90/30 Source Gap: 5 traces (125 m) Near Trace Offset (short arm): 787.5 m Far Trace Offset (long arm): 2287.5 m Element Spacing: 3.4 m

Table 3-11. Seismic parameters used for the 1991 data acquisition in the northern Mount Isa Basin (tabulated from Meaney et al., 1992)

3.8.1 Structure

Several major faults are present throughout the northern Mount Isa Basin. Blake (1987) identified four of significance either within or bounding the Riversleigh Fold Zone. None of these faults extends into the Bowthorn Block where the ATP 423P seismic program was undertaken.

Significant structuring is present both within and bounding the Bowthorn Block of the northern Mount Isa Basin. These comprise early down-to-the-north normal faults that have been reactivated episodically by thrust inversion producing structures such as at Egilabria-1, Desert Creek-1 and Argyle Creek-1. The northern Mount Isa Basin is only highly structured in the south, with the greatest amount of foreland deformation occurring during pre-South Nicholson Group time south of the Elizabeth Creek Thrust, and post South Nicholson Group time within the Bowthorn Block itself. The structure at Century appears to be dominated by low angle, bedding plane thrusts and extensive local deformation. Ore boundaries are typically stylolitic or fault contacted.

From the regional dip line to the south of Connolly Valley (Figure 3-29b; Enclosure 6) it has been possible to stereographically calculate the average dip directions for the different basin sequences. Basement and the rift and passive margin sequences dip regionally to the south while the overlying foreland sequence dips southwest. This clear change in structural attitude suggests a significant provenance direction change in the basin at the time of plate collision and major compression when the foreland system was initiated.

Seismic data collection over Connolly Valley was unsuccessful because the sections over the structure failed to prove closure at depth, greatly diminishing the prospectivity of the target (no coherent data could be obtained from the Connolly Valley area). Such is the influence and importance of the seismic method that failure to be able to extrapolate exploration drillhole lithology information that might be gained from a drillhole at Connolly Valley to the surrounding seismic grid was sufficient reason to not consider drilling in the area at an early stage of basin evaluation.

Two reasons can be suggested for the lack of coherent data from Connolly Valley. The first is faulting. As both the north and south sides of the valley are clearly fault controlled it is quite possible that a zone of chaotic fracturing exists both within and next to the valley. This is consistent with the poor data observed over other fault zones notably the Elizabeth Creek Fault Zone and the northern end of Seismic Line 89BN-06. The lines shot perpendicular to the valley at the eastern end, seismic lines 91BN-19 and 91BN-30, indicate that the valley may comprise a major fault zone. The second possible reason is poor surface ground conditions around Connolly Valley. In this situation loose shallow soil acts as an energy absorbing layer dispersing and distorting the input signal. The correct interpretation is important to determine in this situation because if faulting is the cause then reshooting the survey with different acquisition parameters and energy source can be expected to result in little improvement to data quality. Based on the various studies described above it seems probable that Connolly Valley is a major normal fault zone originally downthrown to the north about 2 km and later reactivated by compression.

3.8.2 Seismic events

Regional seismic data from the northern Mount Isa Basin sequence has been obtained only from the less structurally deformed northern portion of the basin lying north of the Elizabeth Creek Thrust Zone. The regional basin analysis seismic sections are illustrated in Figure 3-29 (a-d) and Enclosure 6, and located in Figure 3-30. Within the Bowthorn Block, 15 prominent unconformities have been mapped, although more are present. These represent the most widespread coherent reflectors that can be readily traced throughout the existing seismic grid. Events showing clear regional continuity are all unconformities. The unconformities mapped as a series of sequence boundaries are shown in Table 3-12. Each seismic package thickens towards the south, but the thickening is most prevalent within the middle and upper portions of the stratigraphy. The most prominent reflectors appear to be unconformities and acoustic impedance contrasts between thin carbonate units that have high relative velocities and the mostly clastic sequence.

Basin	Seismic Events	Lithostratigraphic Level	Comments
Carpentaria Basin	T	Base of Allaru Mudstone (Near top Toolebuc Fm)	Clear pick
	G	Base of Wallumbilla Fm (Near top Gilbert River Fm)	Clear pick
	J	?Base of Carpentaria Basin *sensu stricto* (Near top Pre-Jurassic)	Not shown on compressed sections and difficult to resolve from Z at full scale
	Z	Base of Mesozoic (?Pre-Jurassic), possibly top of Proterozoic	Most prominent reflector in section
Northern Mount Isa Basin	A	Base of South Nicholson Group	Clear pick
	B	Intra- Lawn Hill Formation	Clear pick
	C	Base of thin widespread limestone, believed to correlate to the Doomadgee Formation (?Intra-Termite Range Formation)	Clear pick
	C_1	Intra- Termite Range Formation	Only recognised on 1991 data
	C_2	Intra- Termite Range Formation	Only recognised on 1991 data
	Y	Intra-Riversleigh Siltstone	Only recognised on 1991 data
	X	Intra- Riversleigh Siltstone	Long standing unconformity
	X_1	Intra- Riversleigh Siltstone	Only recognised on 1991 data
	D	Intra- Riversleigh Siltstone	Clear pick
	D_1	Base of Riversleigh Siltstone (and Shady Bore Quartzite; near top of carbonate dominated section)	Characteristically overlain by a package progradational to the north throughout the southern Bowthorn Block
	E	Base of Lady Loretta, Esperanza and Paradise Creek Formations	Good resolution on 1989 compressed sections and all 1990 and 1991 data
	E_1	Base of McNamara Group (Base of Gunpowder Creek Formation and Torpedo Creek Quartzite)	Poor regional continuity
	E_2	?Intra basal volcanics	Poor regional continuity
	F	Base of volcanics and volcaniclastics - top basement (base of the northern Mount Isa Basin)	Difficult to resolve on 1989 and 1990 full scale sections, clear on 1991 data

Table 3-12. Seismic stratigraphic events

The seismic sections are displayed in SEG normal format. This results in an acoustic impedance contrast from a low velocity to an underlying higher velocity layer being displayed as a trough (white on the sections). The variable area peaks are displayed with black fill for contrast. No bias was applied as the contrast was well balanced. The seismic ties to the 1992 petroleum drilling were detailed in Barlow and McConachie (in press).

3.8.3 Seismic stratigraphy

Seismic sequences were defined by Mitchum et al. (1977) as a "relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities". A wide range of unconformity surfaces have been observed on the seismic data. The unconformities and their equivalent surfaces mapped within the northern Mount Isa Basin alter in character into and out of the basin becoming disconformities or even conformable surfaces. Using the ideas of seismic stratigraphy it was possible to recognise package boundaries that range from angular unconformities to their correlative conformable surfaces dependant upon depositional rates and styles in different basinal areas.

The depositional sequences or seismic stratigraphy of a sedimentary basin are complex responses to tectonic and eustatic controls and this is particularly dramatic foreland sequences (Karner, 1986; Heller et al., 1988). The events recognised in the northern Mount Isa Basin have evolved throughout the life of the seismic acquisition program due mainly to variations in data responses in different areas. The breakthrough in the understanding of the seismic stratigraphy of the Mount Isa Basin came with the acquisition of the composite regional dip line to the south of Connolly Valley (Figure 3-29b; Enclosure 6). This line provided very valuable structural information, confirmed the predicted model for basin architecture, and most importantly, it radically altered the postulated basin seismic stratigraphy from the ideas implied by the original

1989 seismic data that did not suggest significant truncation of major seismic stratigraphic units at the northern basin margin.

From the full data set, the most prominent and widespread unconformities (and their equivalent conformable surfaces) were labled A through to F with some extra events added later using letters and numbers. These were identified on the composite line of section south of Connolly Valley, at the western edge of the ATP 423P seismic grid and from several other lines in the area. The uppermost event affecting the Mount Isa Basin is the Z horizon. This horizon is the base of the Carpentaria Basin unconformably overlying the Mount Isa Basin. The basement event for the Mount Isa Basin was named F. All the mapped horizons and events delineate seismic sequences that are shown on Table 3-13.

The seismic stratigraphic interpretation of the various seismic packages had to incorporate two important observations:

The first was the pinchout of much of the A to D1 packages south of Connolly Valley resulting in their absence at the projected site of outcrop. This is opposite to the situation observed in the eastern seismic grid where all the seismic packages A to F are cut by the base of Mesozoic unconformity due to late uplift of the eastern part of the basin. This means that the field mapped stratigraphy reported by Dunster and McConachie (1990) represents a highly condensed portion of the full subsurface stratigraphy.

The second observation was that the stratigraphy which is reported by McConachie et al. (1991 a and b) in the Riversleigh Fold Zone near Elizabeth Creek can be extrapolated to the seismic data showing that the bulk of the seismic section correlates to the upper McNamara Group. This comprises four formations namely the Shady Bore Quartzite, the Riversleigh Siltstone, the Termite Range Formation and the Lawn Hill Formation, a total stratigraphic interval of some 6000 to 7000 metres that occurs south of the Elizabeth Creek Thrust.

From the above analysis it can be determined that the Mount Isa Basin contains syn-rift, passive margin and peripheral foreland sequences as illustrated on the regional seismic dip cross-sections presented in this thesis (Enclosure 6). Each of the many seismic packages in Table 3-13 and lithostratigraphic packages described previously are contained within these sequences. Detailed seismic lithologic interpretation of the kind undertaken by Fontaine et al. (1987) was not possible due to the lack of lithostratigraphic control, however with further outcrop studies and detailed work on the petroleum drillholes a detailed seismic-lithostratigraphic model of the Bowthorn Block of the northern Mount Isa Basin should be possible.

SEISMIC STRATIGRAPHY				LITHOSTRATIGRAPHY						SEISMIC STRAT.
				Lithostrat. Tie						
Sequence	Upper Boundary	Lower Boundary	Seismic Character	O	B	D	A	E	Formation/ (Unit-1992 drilling)	
Z - A	Top of Proterozoic - Major acoustic impedance contrast, obvious erosional unconformity at base Mesozoic and base Cambrian in outcrop	Unconformity at the base of the South Nicholson Group (angular in the Riversleigh Fold Zone, possible paraconformity in the Bowthorn Block)	Parallel reflectors with no seismic evidence of basal unconformity	x x x x x x			x x	x x x x x x	South Nicholson Group (10)	
A - B	Acoustic impedance contrast at the base of elevated palaeotopography (see seismic sections 89BN-06 and 89BN-07, Enclosure 6) ?onlap	Probable unconformity but difficult to recognise due to lack of coherency of internal reflectors ?onlap	Parallel reflectors with no seismic evidence of top or basal unconformity	x x x	x x x x			x x x x x x	Lawn Hill Formation (9)	
B - C	Mostly concordant, possible onlap but data quality is poor	Distinct onlap particularly in the deeper southern part of the Bowthorn Block	Parallel reflectors thickening to south	x x	x x x	x x x	x	x x x x	Lawn Hill and Termite Range Formations (8)	FORELAND
$C - C_1$	Mostly concordant	Onlap	Parallel reflectors thickening to south	x x	x x x	x x x x	x x x x	x x x	Termite Range Formation and Riversleigh Siltstone (7&6)	
$C_1 - C_2$	Mostly concordant	Onlap	Parallel reflectors thickening to south	x x		x x x x	x x x x		Termite Range Formation and Riversleigh Siltstone (5)	
$C_2 - X$	Mostly concordant	Minor onlap	Parallel reflectors thickening to south	x x		x x x	x x		Riversleigh Siltstone (4)	
X - D	Rugose erosional event possibly indicative of differential erosion on palaeotopography	Distinct onlap particularly in the deeper southern part of the Bowthorn Block	Parallel reflectors thickening to south	x x		x x x x	x		Riversleigh Siltstone (3)	
$D - D_1$	Onlap surface, some possible erosion	Erosional truncation at northern basin margin, pronounced onlap surface with some down-cutting observable on full-scale sections	Parallel reflectors thickening to south	x ? x ? x ? x ?		x x x			Riversleigh Siltstone and Shady Bore Quartzite - latter not observed in the Bowthorn Block (2)	
$D_1 - E$	Some erosional truncation of events, most prominent at the northern basin margin	Erosional truncation at northern basin margin	Rare possible mounding	x x x x x		x x	x x		Lady Loretta, Paradise Creek, Esperanza Formations (1)	PASSIVE MARGIN
E - F (E_1, E_2)	Erosion most prominent at the northern basin margin	Erosional truncation at northern basin margin	Parallel and some chaotic reflectors some rapid terminations	x x x x					Peters Creek Volcanics	RIFT

Table 3-13. Seismic sequence stratigraphy of the northern Mount Isa Basin

O - Outcrop; **B** - Beamesbrook-1; **D** - Desert Creek-1; **A** - Argyle Creek-1; **E** - Egilabria-1
X - Present; ? - Possibly present; BLANK - Absent (condensed section)

The basis of the seismic stratigraphy is illustrated in Figure 3-31 from Bally (1989). Falvey (1974), in his paper on the development of continental margins in plate tectonic theory, illustrated the relationship between rift and passive margin sequences during the drift phase. In the northern Mount Isa Basin the rift sequence consists of basal continental tholeiitic volcanic rocks intercalated with clastic and minor carbonate rocks. Overlying drift phase sedimentation comprised shallow-water platform carbonate rocks and their deeper-water equivalents. The upper sequence consists of a mega-coarsening upward and shallowing upward cycle of reworked carbonate rocks and turbiditic fine grained clastic rocks grading upward to shelfal and fluvial deposits comprising mudstones, siltstones and quartzose sandstones with chamositic oolitic ironstones (a flysch-molasse sequence). The stratigraphy within the basin is believed to represent a full Wilson Cycle (Dewey and Burke, 1974). This agrees with the tentative conclusion of Ellis (1992) on the northern Australian granulite terrains (believed to be part of the Carpentarian Superbasin).

3.8.4 Applications

Probably the major benefit from the recognition of the three basic seismic stratigraphic packages within the Bowthorn Block of the northern Mount Isa Basin is that more meaningful geological interpretation in the southern Mount Isa Basin should be possible. This can be achieved by relating the known lithostratigraphy to the major Bowthorn Block packages that from the current work, are now well constrained.

Neudert and Russell (1981) reported shallow water and hypersaline features from the Upper Mount Isa Group near Mount Isa. Neudert (1983) in his detailed study of the Upper Mount Isa Group reported predominantly northerly palaeocurrent directions within this sequence. He concluded that the Lower Mount Isa Group, which is mostly siltstone could have had either a deep or shallow water origin as no definitive shallow water features had been observed.

The Mount Isa Group appears to correlate with the flysch-molasse foreland basin sequence observed in Bowthorn Block, with the Mount Isa mineralisation at about the same stratigraphic level as Century. The Surprise Creek Formation, Fiery Creek Volcanics and Bigie Formation probably represent the earliest foreland units. The Quilalar Formation appears to correlate with the passive margin sequence while the Myally Sub-group Eastern Creek Volcanics, Mount Guide Quartzite and Bottletree Formation could be the rift phase deposits equivalent to the Peters Creek Volcanics (refer to Figure 3-6).

3.9 EVOLUTION

The thermal subsidence and hydrodynamic histories of the Mount Isa Basin can be interpreted from the basin data by use of the uniformitarian and superposition axioms. Each of these aspects is dealt with in connection with the economic geology of the basin in Chapters 5 and 6. The subsidence history of the basin is different for each of the major phases of the basin evolution. The thermal and hydrodynamic histories are linked and the rift and passive margin phases are overprinted by the foreland basin development. The thermal history based on the drilling data in the Bowthorn Block indicates erratic heating through the sedimentary sequence, characteristic of hydrothermal heat transfer (Figure 5-2).

3.10 IGNEOUS ACTIVITY

The igneous activity within the Mount Isa Basin is comprehensively reported in Blake (1987). The major intrusions are illustrated diagrammatically in Figure 3-6 and geographically in Figure 3-32. The major syn-depositional intrusions in the exposed basin comprise the Weberra Granite, Sybella Batholith, Sybella Microgranite, Wonga Batholith, Wonga Microgranite, Lunch Creek Gabbro and the Williams and Naraku Batholiths. These rocks cover a range of compositions from acid to basic with many mafic dykes also being present (Figure 3-19). Blake (1987) reported that the igneous rocks are bimodal with respect to silica content and this characteristic is believed indicative of intracratonic rifting.

Most of the major intrusions were emplaced during the rift phase sedimentation, but pre-, syn- and post-tectonic types have been recognised (Wyborn and Page, 1983; Wyborn, 1988). Tholeiitic volcanism also occurred within the early rift phase of the basin.

During the later passive margin and foreland phases of the basin, the only major igneous bodies that intruded the basin were the Williams and Naraku Batholiths.

During the peripheral foreland phase of sedimentation minor tuffaceous volcaniclastic rocks were deposited within the Lawn Hill Formation of the northern Mount Isa Basin.

Jaques et al. (1982) reported that the regional metamorphic isograds in the Selwyn Range area near Pegmont, were unrelated to the granitoids, most of which show some petrographic evidence of metamorphic recrystallisation. Whether the major intrusions pre-date or post-date the formation of the Mount Isa Basin, characteristics such as the gravity high under the Kalkadoon-Leichhardt Block suggest the intrusions are small scale, high level features typical of rift or orogenic systems. Dr. M.D. Muir, (pers. comm., 1993) stated that the Naraku Granite is unconformably overlain by the Mount Isa Basin sequence at Dugald River and that any intrusions into the basin must belong to another phase or possibly be a different granite altogether.

3.11 PLATE TECTONIC MODEL

The lithosphere of the earth today consists of six major and many minor plates. The major plates are the Eurasian, African, Australian, North American, South American and Pacific plates. Most comprise both oceanic and continental crust except the Pacific which is predominantly oceanic, and the Eurasian which is mostly continental. Each is about 10 000 km across. This type of palaeogeographic distribution appears to have been common throughout the Earth's history including the Proterozoic. Periodic formation of supercontinents was typically followed by breakup.

The present distribution of crust of Archaean and Proterozoic ages is illustrated in Figure 3-33. This shows the persistence of continental crust through time with only a relatively small proportion having been accreted in the Phanerozoic.

Armstrong (1991) highlighted the important point that the implications of plate tectonics extrapolated to a Proterozoic setting, provide an excellent model to replace the concept of crustal growth. Armstrong's alternative model comprised a steady state continental volume that has been accreted and redistributed throughout the Earth's history, but with a declining crust-mantle recycling rate. Howell (1989) compared the many models of crustal growth (Figure 3-34) including that of Armstrong. For comparison, the span of the Mount Isa Basin is superimposed on Figure 3-34. All the models shown predict the substantial completion of crustal growth by the commencement of the Palaeoproterozoic at 2500 Ma. Therefore it is necessary to consider the evolution of old major basins in terms of Wilson Cycles. (Compare this with Dewey and Spall, 1975).

The concept of Phanerozoic style plate tectonic movement throughout the Proterozoic is supported by interpretations and descriptions of many Proterozoic sequences throughout the world. Stanley (1986), after Hoffman (1973), presented a well documented example from North America (see also Section

3.4.8, Proterozoic foreland basins). Another compelling plate tectonic model for the Kilohigok Basin (Grotzinger and McCormick, 1988) was based on flexure of the early Proterozoic lithosphere at 1.9 Ga in the Northwest Canadian Shield. When considered with the evidence from other Proterozoic Basins in Australia, the irresistible conclusion is that plate tectonics as it is understood in its modern context, was fully operational throughout the Proterozoic Era. Over recent years Burke et al. (1986), Eriksson et al. (1988) and de Wit et al. (1992) have described a full plate tectonic model for the late Archaean Witwatersrand Foreland Basin.

The styles of subduction thought to be common in the Archaean, Proterozoic and Phanerozoic were described by Meissner (1986). The predominant style in the Proterozoic was considered by him to be A type subduction with thinner faster oceanic plates exhibiting little negative buoyancy compared to Phanerozoic examples. It is important to note, however, that both type A (Chilean) and type B (Mariana) subduction occur throughout the world today. Using the work of Stockmal et al. (1986) the regional metamorphism at Mount Isa suggests Andean scale mountains of about five to ten kilometres height. Andean (type A subduction) margins show net convergence unlike type B zones. Thus type A zones can be expected to be more commonly associated with continental collisions and low pressure metamorphism.

Hoffman (1989), in his work on the Precambrian geology and tectonic history of North America described the Archaean provinces as welded by early

Proterozoic collisional orogens. The orogens are characterised by deformed passive-margin and foredeep sedimentary prisms, and foreland thrust-fold belts. Their hinterlands, bordered by Andean type magmatic arcs, have regions of basement reactivation, thrusting and transcurrent shearing accommodating collisional foreland indentation.

General evidence of lateral accretion of Proterozoic crust analogous to that in the Phanerozoic Canadian Cordillera is provided by Samson and Patchett (1991) who also highlighted the difficulties of interpreting Proterozoic sequences of equivalent complexity where biostratigraphic control is lacking. They described the correspondence between the main features requiring explanation in Proterozoic belts and the features exemplified by the Canadian Cordillera as striking. Of particular interest, concerning the rocks of the Carpentarian Superbasin, Samson and Patchett recorded the negative ϵ_{Nd} (see abbreviations list) of Australian rocks of this age (Figure 3-35). This feature is characteristic of Phanerozoic orogenic belts.

Throughout earth history many changes and interactions have occurred to shape the plates to their present configurations, and several major chelogenic cycles have been recognised. Rutland (1981) described three chelogenic cycles that have established the Australian Plate as we see it today. These are the Archaean cycle corresponding to the West Australian Orogenic Province, the Palaeo and Mesoproterozoic cycle including both the North Australian and Central Australian Orogenic Provinces, and the late Precambrian to Phanerozoic cycle of the Tasman Orogenic Province. Within each long-term chelogenic cycle, plate tectonic schemes interpretable in terms of the Wilson Cycle can be distinguished. Both the Archaean and Proterozoic orogenies seem analogous to those of the Phanerozoic where the plate tectonic context is clear.

Rutland (1981) considered that although orogenic belts were broad during the major orogenic phases of the Proterozoic Australian plate development and largely ensialic, they were probably developed in back-arc environments adjacent to continental margins. When combined with the ensialic nature of the Proterozoic cycle, it could be inferred that the continental crust of the Proterozoic province was only partially the result of lateral accretion during the Proterozoic chelogenic cycle. It is also the product of vertical sedimentary basin accretion in the Proterozoic, both on and within pre-existing Archaean proto-continental crust.

Many authors have attempted to identify the basin character of the rocks of the Mount Isa Basin. Most have concentrated on the highly faulted area near Mount Isa. Even when regional reconstructions have been attempted (e.g. Wellman, 1992; Plumb et al., 1981; Bourke et al., 1988) these have largely used ambiguous potential field geophysical data to project preconceived ideas based on the highly deformed area near Mount Isa.

Glikson et al. (1976) described the tectonic evolution and crustal setting of the Mesoproterozoic Leichhardt River fault trough. They found that the geochemical features of the Eastern Creek Volcanics are consistent with those of continental flood tholeiites while to the east near Cloncurry, ocean floor type tholeiites occur. In addition, the absence of alkaline volcanic rocks in the Leichhardt River fault trough was seen as inconsistent with a rift valley model for the fault trough.

Derrick (1982, 1983) interpreted the Leichhardt River Block (fault trough) as a Proterozoic rift system (see also Wyborn and Blake, 1982). The trough was defined as a major, basalt filled, linear crustal feature some 60 km wide, extending for some 600 km from near Lawn Hill to the Cork Fault based on aeromagnetic extrapolation. This fault trough was described as located near the margin of the Pan-Antarctic craton. Interestingly, Derrick (1982; p84, Figure 5) illustrated Proterozoic compression within the postulated rift sequence not the tensional faulting that would be expected if the rift model were truly applicable (Bonatti, 1987; Mutter, 1986; Veevers, 1981). Gunn (1983) also proposed the Leichhardt River Block as a rift zone.

Blake (1980) recognised the significant differences between the Western Succession (Leichhardt River Block) and the Eastern Succession (Mary Kathleen Block). The difficulties in making such a comparison, however, include disconformities, igneous intrusions of various ages, tight isoclinal folding, intense faulting and regional metamorphic effects. Blake (1987) compiled the major regional data throughout the Mount Isa Basin. He described the two contrasting models for the Proterozoic tectonic setting of the area as being intracratonic and continental margin. He concluded that an intracratonic setting was the most probable, but did not consider the question of the basin model which he assumed to be a rift.

Further developments on the rift theme, included the recognition by several authors of one or more supposed thermal relaxation sag phases that post-dated the rifting (e.g. Jackson et al., 1990). Williams (1989) described the nature and timing of early extensional structures in the Mitakoodi Quartzite near Mary Kathleen and Connors et al. (1992) described an east-west syndepositional normal fault south of Mount Isa.

The precise cratonic setting of the Mount Isa Basin is probably less relevant if a foreland model is considered. Although fore-arc and retroarc styles occur, foreland basins at continental margins can grade cratonward into intracratonic settings e.g. the Arkoma-Illinois Basins. The Papuan peripheral foreland basin is located close to the margin of the Australian Craton yet is continuous with the Carpentaria-Eromanga system.

Oliver et al. (1991) described the tectono-morphic evolution of the Mary Kathleen Fold Belt in terms of early lithospheric stretching followed by compression. The stretching was reported as occurring due to north-south extension with the subsequent compression east-west. They also noted that there exists strong synchroneity of age groupings across many Australian (and Antarctic) Mesoproterozoic regions.

The style of basin that best explains the range of data available from the geological section in the northern Mount Isa Basin is a rift-drift-asymmetric peripheral foreland model. This is supported by a range of evidence including palaeocurrent directions (e.g. Sweet, 1985; Neudert, 1983), isopachs, basin thickness, subsidence rate, architecture, vertical lithostratigraphy and structural style as determined from both seismic data, drillholes and outcrop.

Based on the analogues previously referred to (Section 3.4.7, Basin analogues applicable to the Mount Isa Basin), there are three structural deformational styles associated with the late foreland basin stage. These relate to the decrease in deformation away from the orogenic zone. From the feather-edge a series of flat, folded and highly deformed rocks can be identified in most foreland basins. In the Mount Isa Basin these correspond to the Bowthorn Block, Riversleigh Fold Zone, and probably the Cloncurry Orogen (McConachie et al., 1993).

The most controversial aspect of the basin model proposed in this thesis is the inclusion of a foreland sequence within the Mount Isa Basin. The factors that conclusively point to the foreland (lithospheric flexural) style of the Mount Isa Basin are:

1. The syndepositional compressional tectonic regime. This is clear in the Mount Isa area where syndepositional compression is shown on many cross-sections, in the Lawn Hill area where thinning over compressional folds occurs,

and on seismic sections at the northern basin margin where the Elizabeth Creek Thrust is a major syn-depositional compressional feature.

2. The asymmetric architecture of the Mount Isa Basin which comprises a wedge thickening from 1 km of stratigraphic section at the northern basin margin to 10 km in the Lawn Hill area, and an estimated 15 km near Mount Isa (based on the evidence of maximum metamorphic grade reported by Blake, 1987) with no evidence of thinning on the southern flank. The pronounced south to north thinning and sequence progradation is evident on the seismic data within the Bowthorn Block (discussed in Section 3.8.3, Seismic stratigraphy).

3. The variation in deformation and metamorphic grades between the northern basin margin and the Mount Isa area so characteristic of forelands and not of rifts.

4. The presence of large stratiform base metal deposits is a feature commonly considered characteristic of hydrothermal brines (e.g. Kesler and van der Pluijm, 1990) that need to be pumped into clastic and carbonate sequences during foreland basin development (unlike in rifts for example where metal-rich brines are expelled onto the sea floor or into volcaniclastic dominated sequences).

5. The thickness of the deepest part of the basin which exceeds the maximum theoretical depth for any rift model based on lithospheric stretching (Allen et al., 1986).

6. The high subsidence rate producing deep water sedimentation in the proposed early foreland phase.

7. The tectonically related major unconformity surfaces at the northern basin margin characteristic of a foreland feather edge and peripheral bulge, with pronounced erosion during the period of rapid subsidence in the south.

8. The absence of calc alkaline volcanic rocks within the proposed foreland sequence.

9. The upper stratigraphic sequence (proposed passive margin and foreland) that comprises shallow water platform carbonates overlain by flysch and finally molasse sequences is typical of forelands and not rifts.

The presence of greenstones in the southern Mount Isa Basin, and serpentinites at Broken Hill and Georgetown suggests a marginal plate tectonic setting for these areas. It must also be remembered that plate tectonic evolution involves models that are not simple jig-saw puzzles, but Lego-like constructions that can be correctly assembled in many ways, but with only one of the equally correct assemblies having actually occurred (Miall, 1984). Murphy and Nance (1992) provided an account of the supercontinent breakup cycle that possibly extends back to the Palaeoproterozoic. Murphy and Nance (1991) described the Neoproterozoic plate tectonic setting (Figure 3-36; see also Young, 1992; Davidson, 1992). This is about the oldest reliable geological plate reconstruction that has been made. Moores (1991) presented a speculative Palaeoproterozoic plate tectonic setting based mostly on correlations between USA and Antarctica (Figure 3-37). The interesting aspect of his reconstruction is the juxtaposition of the Carpentarian Superbasin and the very similarly aged Wopmay Orogen described above. Remembering that the Wopmay Orogen is interpreted as a Palaeoproterozoic retroarc foreland basin and the Carpentarian Superbasin is a peripheral foreland basin and these may be related as shown in Figure 3-16.

Lambert (1983) described the major lead-zinc deposits of the Proterozoic including Sullivan, a stratiform deposit similar in age and character to the mineralisation of the Carpentarian Superbasin. The Sullivan deposit is located in the Canadian Cordillera in western central Canada.

Howell (1989) described variations in crustal thickness as depending upon the location within continental plates. Thickness is greatest in shields and convergent orogenic zones. Australian crustal thickness has been estimated by Wellman (1976). Figure 3-38 presents the data related to the Mount Isa Basin. From this figure it can be seen that crustal thicknesses exceed 35 km and are thicker than average at both Mount Isa and Broken Hill but are thin in the failed rift between the two areas. Stevens et al. (1988) looking at possible origins for the Willyama Supergroup at Broken Hill considered that this area could be placed into a plate tectonic setting only with great difficulty, but they provided the questions to enable the problem to be solved. The lack of a suture zone is probably due to Neoproterozoic transfer fault displacement south of Broken Hill. The mechanism for strong compression is plate collision which can produce both thick skin and thin skin compression under different circumstances. Finally, as P.F. Hoffman (referred to in Stevens et al., 1988) considered -- seafloor spreading (and consequent subduction if the Earth is not to expand quickly) is the most efficient known and obvious mechanism to enable heat flow from the mantle.

To conclude, it is probable that the Mount Isa Basin was initiated by rifting at about 1800 Ma corresponding to the Hudsonian event in North America. Drift with passive margin development probably took place between 1670 and 1620 Ma. Foreland development probably began with collision of the proto-Australian Plate with the proto-North American Plate at around 1610 Ma following subduction of the intervening oceanic crust under the North American Plate. Breakup or a change in stress directions then resulted in overprinting of the original north-south collision with east-west compression. Throughout much of the remainder of geological time to today -- minor failed rifting (Warburton and Cooper Basins), breakup producing the proto-Pacific Ocean (Young, 1992) and the accretion of eastern Australia all occurred leaving the northern Mount Isa Basin relatively little disturbed except for steady erosion and deeper exposure of the orogenic highlands. Due to its proximity to the above events, the southern Mount Isa Basin was more affected by the tectonic disturbances and deeper burial in both the Neoproterozoic and the Palaeozoic Eras. The Palaeo- to Mesoproterozoic development of the Mount Isa Basin is believed to have occurred as illustrated in Figure 3-39.

4 ECONOMIC GEOLOGY OF THE MOUNT ISA BASIN

4.1 INTRODUCTION

The purpose of this chapter is to introduce the following two chapters on the hydrocarbon and metal geology of the northern Mount Isa Basin. The idea of commodity provinces has long been understood in the geoscience industry. Under the presence of favourable conditions vast accumulations of either hydrocarbons or metals can be deposited within definable geological entities. The level of the definable entity may be at either the plate tectonic superbasin, basin, or sub-basin scales.

4.2 HYDROCARBON AND METALLOGENIC PROVINCES

Wright (1990) recently described basin mineralisation for base metals, copper and gold in terms of petroleum exploration concepts to account for various major metal provinces of the world. The major metal type-provinces he distinguished were:

Mississippi Valley, Laisvall, shale hosted, and Irish type base metals;
Kupferschiefer copper-gold;
Lufilian Fold Belt (Zambia) copper-cobalt, uranium-gold and noble metals;
and Witwatersrand gold mineralisation.

Pavlov et al. (1991) described the association of stratiform lead-zinc deposits, oolitic iron ores and oil and gas basins. They considered that this association was confined to areas where ascending ground waters were discharged in the basins. They also included red-bed copper, gold-sulphide, mercury and manganese deposits in the association. Evidence for the association of ores and napthides (their term) was based on the presence not only of spatial but also age relationships between ore deposits and oil producing rocks, the metal content of the oil and gas basin ground waters, the importance of organic matter in the formation of ores and napthides, the presence of petroleum hydrocarbons in the ores, the presence of neogenic minerals typical of the ores and wall rocks of sulphide deposits, together in the permeable rocks of oil and gas basins.

The association of metals and hydrocarbons is complex and may be coincidental as opposed to genetic (Gize, 1989). Because many metals seem related to higher temperature fluids than hydrocarbons, it is difficult to see the two commodities forming by the same process unless it occurs in different parts of the same basin where different conditions prevail. Because hydrocarbons will tend to form first in any geothermal regime, the genetic relationship is likely to be confined to fluid interactions related to deposition. Although low temperature precipitation conditions prevailed during the formation of many base metal deposits, locally heated immature source rocks have sometimes produced small uneconomic oil and gas shows commonly observed in nearby drillholes (e.g. MacQueen and Powell, 1983).

Metal and hydrocarbon deposits are different in several obvious ways that greatly affect their respective preservation potentials within sedimentary sequences. Although they are commonly found in and produced by the processes within sedimentary basins, at common basin temperatures and pressures, hydrocarbons are liquids or gases while metals (other than mercury) are solids. The capacity of gas therefore to leak or diffuse, and for oil which is unstable on a kinetic basis to be geochemically or biologically degraded, is much greater than for metals. Metals such as iron may even be precipitated by biological action. Therefore, once a hydrocarbon field exists, the entropic forces of nature are potentially much more damaging than for metal deposits.

Hydrocarbon provinces may occur over large geographic areas and wide time spans such as in the Middle East, or along trends, for example a hinge line next to a deep basin where a single regional reservoir unit is deformed to produce entrapment structures. Metallogenic provinces can occur over the same range of basin or sub-basin scales dependent upon the conditions for generation and entrapment. These are the elements that the analysis in the following two chapters seeks to address.

Although the concept of crustal growth proposed by Stanton (1972) has been superseded by plate tectonic concepts, his hypothesis relating ore types to the "normal" sequence of events in what can now be recognised as various basin types, is the framework within which the hydrocarbon and metallogenic province of the northern Mount Isa Basin fit. The multicyclic plate tectonic driven basin evolution, source rock potential for both hydrocarbons and metals, and the common basin geodynamics are the keys to recognising the metal and hydrocarbon province association within basins of any age.

5 PETROLEUM GEOLOGY OF THE NORTHERN MOUNT ISA BASIN

At the outset it was obvious from the large amount of work previously undertaken exploring for minerals within the Mount Isa Basin, that only the northern basin margin retained any petroleum potential, and this chapter is primarily focussed on that region.

5.1 THE WORLD PETROLEUM SCENE

Many of the worlds great oil producing basins formed as peripheral foreland basins. Many Phanerozoic Mount Isa Basin analogues that were described previously contain vast reserves of oil and gas.

Barker (1985) and Selley (1985) described the volumes of commercial oil accumulated under various conditions such as age, type of structure, reservoir composition etc. Based on their observations it is obvious that only a small fraction of the world's commercial oil is contained in Proterozoic rocks. This undoubtedly relates to both the area of well preserved Proterozoic basins and the hostile conditions for oil stability to which many of these basins have been subjected.

Miller (1992) described the global oil system on a theoretical half life basis as containing 4 trillion bbls. This quantity was derived using a half-life of 29 Ma assuming global generation of 2.7 MM bbls yr^{-1} with 0.8 MM bbls yr^{-1} entering reservoirs. Geological analogues predict only about 2 trillion barrels. Using the mass balance data of Miller, nearly all the worlds reservoired oil is less than 350 Ma old and was generated from source rocks extending back 550 Ma. These ages are very young compared to the Mount Isa Basin's approximately 1800 to 1600 Ma age span.

5.2 The Australian petroleum scene

Australia has no known commercial accumulations of Proterozoic oil and gas, but several sub-economic finds have been made. The most significant of these is the Dingo Field in the Amadeus Basin of central Australia. This is a 60 BCF dry gas field reservoired in Neoproterozoic sandstone. The other area with substantial oil and gas shows is the Palaeo- to Mesoproterozoic McArthur Basin. Bitumens, live oil and gas have been recorded from various stratigraphic levels within this basin (Muir et al., 1980; Jackson, 1985; Jackson et al., 1988).

5.3 Proterozoic hydrocarbons

The possibilities that Precambrian sedimentary sequences hosted and still contain major hydrocarbon accumulations increases in importance as conventional non-OPEC oil reserves dwindle. Source rock deposition undoubtedly occurred in Proterozoic sequences (from the time of eukaryote algae evolution and before grazing organisms, first order heterotrophs, evolved), but the potential for early generated oil and gas to exist in commercial quantities today is difficult to assess on an untested theoretical basis. Pratt et al. (1992) described widespread layered sedimentary rocks aged between 2.0 and 1.3 Ga and underlying large areas of Mid-continental USA as having important and untested hydrocarbon entrapment potential.

Reservoir quality and trap integrity generally deteriorate with time but, in stable areas preservation conditions may exist. Based on the available seismic data (Enclosure 6), the northern Mount Isa Basin, although interpreted to have formed in an active tectonic setting appears to have undergone little subsequent deformation. Kroos et al. (1992) quantified gas leakage from reservoirs and this is discussed under Section 5.4.9, Preservation.

Murray et al. (1980) provided an overview of Precambrian fossil sequences and associated hydrocarbon deposits throughout the world and noted that the basic components of petroleum have existed since the early phases of the Earth's history. Three main areas of the world are known to contain economic Proterozoic hydrocarbons. They are Oman, the Siberian Platform of the Commonwealth of Independent States and the Sichuan Basin of China. Each of these areas has been reviewed by Walter (1992a) and although some aspects can be related to the Mount Isa and McArthur Basins, in many substantial ways all three areas are quite different to any known areas of the Carpentarian Superbasin.

Husseini (1989) described the tectonic and depositional model of the Neoproterozoic-Cambrian of the Arabian and adjoining plates. Wright et al. (1990) described the basin setting of the petroleum bearing Huqf Group. The lithostratigraphy and petroleum geology of Precambrian and Cambrian Huqf Group in Oman has been well documented (Al-Marjeby and Nash, 1986; Gorin et al., 1982; Clarke, 1988). The origin of the crude oils was described by Grantham et al. (1987) and Fritz (1989) who showed that the Precambrian Huqf Group constituted a major oil and gas source.

Meyerhoff (1980) provided details of the geology and petroleum fields in Proterozoic and Lower Cambrian strata of the Lena-Tunguska petroleum province of eastern Siberia. Mandelbaum and Shamal (1990) described the unconventional geophysical exploration techniques used to locate these deposits.

Apart from descriptions by Walter (1992a) there is little information published on the Precambrian of the Sichuan Basin of China.

All three Proterozoic oil and gas producing regions contain Neoproterozoic age rocks rather than the Palaeo- to Mesoproterozoic rocks as in the Mount Isa Basin. Oman contains abundant Proterozoic source rocks and some 1.5 Bbbl of oil reservoired in about 50 major fields. While some oil is reservoired in the Vendian Huqf Formation most is contained in Palaeozoic rocks and late generation is indicated. The situation in the Siberian Platform is similar.

Although most of the oil (largest field 800 MMBbl) is sourced and reservoired in the latest Proterozoic and Cambrian rocks, oil and gas generation within the Proterozoic sequence appears to have occurred in both the Palaeozoic and Mesozoic. In the Sichuan Basin of China, large gas fields (more than 1 TCF) are contained within and sourced from late Proterozoic rocks. Substantial subsidence and probable generation appears to have taken place in the late Proterozoic, Cambrian and Silurian.

5.4 THE PLAY

To understand petroleum exploration it is necessary to distinguish the levels at which petroleum investigations are conducted. Edwards (1992) provided a scheme that has been adapted to the Mount Isa Basin in Table 5-1. All levels are important in a grass roots basin like Mount Isa. Essentially the process involves following Edward's "Philosophy for finding major petroleum accumulations".

Item to be compared	Sedimentary basin	Petroleum system	Play	Prospect
Emphasis	Sediments	Petroleum	Trends and traps	Trap
Geologic time	Time of deposition	Critical moment	Present-day	Present day
Economics	None	None	Essential	Essential
Existence	Absolute	Absolute	Conditional -- requires testing	Conditional -- requires testing
Analysis	Basin	System	Play	Prospect
This study	Mount Isa Basin	Passive margin-foreland-rift	Turbidites sealing shallow carbonates, channel sandstones	Desert Creek-1 Argyle Creek-1 Egilabria-1

Table 5-1. Levels of petroleum investigations conducted on the Mount Isa Basin (based on a concept by Edwards, 1992)

Demaison and Huizinga (1991) described a genetic classification of petroleum systems based upon process driven attributes. They expanded the use of analogues from descriptive tectonic "look-alike" systems to the comparison of genetic "work-alike" systems based on two subsystems. These are a generative subsystem that supplies petroleum controlled by biochemical and thermochemical-kinetic transitions and a migration-entrapment subsystem which focuses and traps migrating hydrocarbons. This genetic classification idea neatly complements the play concept by allowing the recognition of particular play types in different basins (Table 5-2).

Charge factor	Migration drainage factor	Entrapment Factor
Undercharged	Vertically drained	Low impedance
Normally charged	Laterally drained	High impedance
Supercharged		

Note: Mount Isa Basin characteristics shaded

Table 5-2. Organic geochemical basin classification (after Demaison and Huizinga, 1991)

Allen and Allen (1991) defined a petroleum play as a perception or model of how a producible reservoir, petroleum charge system, regional topseal and traps may combine to produce petroleum accumulations at a specific stratigraphic level. To create a play an understanding of both the structural and stratigraphic evolution of the depositional sequences within a basin is essential. This understanding may be achieved through basin analysis, which serves as a springboard for the assessment for petroleum plays.

The Bowthorn Block of the Mount Isa Basin presented a unique and clearly defined opportunity to test a major and quite favourable play for early generated Proterozoic hydrocarbons. In the Mount Isa Basin the primary structural play was shallow water carbonates (Lady Loretta Formation and Walford Dolomite) overlain by thick monotonous fine grained claystones, mudstones and siltstones of the Riversleigh Siltstone and Mount Les Siltstone turbidites. The secondary and more elusive targets in the basin were the sporadic intercalated channel sandstones within the clastic turbidite sequence.

5.4.1 Basin analysis to play concept

Persistence in ATP 423P enabled the Comalco operated joint venture to recognise a unique and very favourable petroleum exploration opportunity in the northern Mount Isa Basin.

The geological criteria upon which successful petroleum plays are based were all thought to be present. These are source, generation, reservoir, seal, migration, structure, timing and the potential for preservation. The foreland geometry of the basin greatly enhanced its potential. Image processing of the magnetic data clearly showed the extent of the prospective margin of the northern Mount Isa Basin similar to exploration in other foreland basins as described for example by Bachmann et al. (1982). To build the petroleum play for the basin it therefore only remained to unify the geological and economic criteria into a model capable of being definitively tested. Beaumont (1991) described the technique.

5.4.2 Source rock

The existence of the remains of microorganisms in the Mount Isa Basin has long been known from studies of the Urquhart Shale (Love and Zimmerman, 1961).

Similar occurrences have been reported from the McArthur Basin (Croxford, et al., 1973) and in formations associated with lead-zinc mineralisation (Hamilton and Muir, 1974) at McArthur River. The microfossils of the Roper Group of the McArthur Basin were reported by Peat et al. (1978). In short, abundant evidence for potential widespread source rock occurrences in the Proterozoic sequences of northern Australia, in states of preservation ranging from immature to overmature, has been recorded over many years (see also the general Proterozoic life discussion, Section 2.6.3).

The presence of hydrocarbons in the McArthur Basin was reported by Muir et al. (1980) and live oil by Jackson (1985, 1986). In the northern Mount Isa Basin, stratigraphic drilling by Dorrins et al. (1983) identified oil bleeds in drillhole Amoco 83-4. Ball (1911) identified bituminous materials containing volatile hydrocarbons in the Lawn Hill Formation in the Riversleigh Fold Zone.

Geochemical measurements

The techniques of polished section petrography and programmed pyrolysis (Peters, 1986; Waples, 1985) were used to evaluate the source rock and maturities from the northern Mount Isa Basin. These results were then compared to and integrated with theoretical calculations based upon burial histories and calculated geothermal gradients and histories. Cull (1982) produced a coarse regional plot of Australian heat flow data that indicated a relatively low geothermal gradient for the Mount Isa area compared to younger sequences such as the Eromanga Basin. This can be compared to the results of Blackwell and Steele (1989) who concluded that the quartz content of rocks is the primary variable determining their thermal conductivities because quartz has the highest thermal conductivity of all the common rock-forming minerals. The highly silicified rocks of the Mount Isa Basin have high thermal conductivities today, but probably lack convective fluid transfer systems resulting in the low heat flows observed.

Reflectivity and source rock studies

Several previous interpretations were confirmed, and new results emerged from the work of Glikson (1990 and 1993).

1. A trend of decreasing maturity to the north was confirmed. This was based on alginite reflectivities within the lower units of the South Nicholson Group, significantly increasing the number of data points and improving the interpretation of the previous measurements. Based on the results it was possible to infer a zone of potential oil preservation in the northern Mount Isa Basin area in ATP 423P and clearly extending into the Northern Territory (Figure 5-1). Interestingly, the only area within the basin where fluorescence in organic matter was observed in the study of Glikson (1990) was confined to uphole samples from Connolly Valley and deeper drillholes northeast of that location. The organic matter in the shallow upholes at the site of the Connolly

Valley structure comprises immature alginite and bitumens with fluorescence (Plate 12, a and b).

During seismic uphole drilling it was also observed that the Corinda area also contains immature source rocks with live oil bleeds from the Walford Dolomite. This implied that oil or more probably gas window maturity levels, could be expected at the target depths for the Walford Dolomite deeper into the basin to the south.

2. From the detailed study of Beamesbrook-1 samples it was possible to conclude that the "carbonaceous horizon" in that well comprises pyrobitumen and was not alginite source rock. Whether the pyrobitumen is a degradation product which forms as a residue of oil generation and expulsion from originally present alginite source rock, or whether this pyrobitumen represented degraded migrated hydrocarbon could not be determined. The pyrobitumen reflectance profile from petroleum exploration wells in the basin (Figure 5-2) may also be significant (Glikson and McConachie, in press). It clearly shows a reflectance peak at the C seismic event level which may be indicative of a previous non-uniform geothermal gradient which could possibly be interpreted as resulting from hot brine movement within the basin. This speculation is necessarily based on pyrobitumen reflectivities as little alginite is present in the deeper portion of the well. The precise variation in reflectance of pyrobitumen with increasing maturity is simply unknown now, but it probably increases in a manner similar to most other macerals. This may mean that the well intersected

highly overmature and degraded, migrated hydrocarbons. Highly carbonaceous units were intersected at the same stratigraphic level in each structure drilled during the 1992 program, although the lithofacies were predominantly siltstone.

The drilling of Desert Creek-1, Argyle Creek-1 and Egilabria-1 during 1992, enabled several hydrothermal events to be recognised on the basis of bitumen and pyrobitumen reflectances. Rapid high-temperature heating produced erratic rank changes within the sedimentary profiles of each of the wells, resulting in the formation of mesophase from pyrobitumen (possibly by the destruction of hydrocarbons) in some samples. The erratic rank variations observed are quite different from theoretical results derived from a steadily subsiding basin model using a constant geothermal gradient. Plate 13 illustrates a range of organic textures observed by Dr M. Glikson in samples from the 1992 Comalco drilling.

3. Macro-organic remains such as stromatolites are typically poor source rocks lacking in lipid-rich pre-cursor hydrocarbon chemicals. Much of the alginite in the sequence however, was produced by a unicellular planktonic alga related to the extant *Botryococcus*, a lipid rich hydrocarbon secreting organism. This was a prolific source rock organism capable of inhabiting marine, brackish and freshwater environments (Dr. M. Glikson, pers. comm., 1992).

$\%R_o$ Alg	Alteration Zone	Stage	Hydrocarbon Generation	Tmax	$\%R_o$ V	Fluorescence
<0.1 0.1 0.2	I	1	under mature		<0.5	yellow
0.3 0.4	II	2	start oil generation	438	0.6	amber-orange
0.5						brown
0.6			peak oil generation	445	1.0	none
0.7 0.8	III		end oil generation	450	1.3	
0.9 1.0	IV	3	wet gas/ condensate mature & stable			
1.1 1.2-1.6	V		end oil preservation	470	1.3-1.6	
>2.0	VI	4	gas generation only		>2.0 anthracite	

Table 5-3. Stages of oil and gas generation based on alginite reflectivities with vitrinite reflectivity equivalents (from Glikson et al., 1992)

4. The alginite window of oil generation is very narrow (0.3 to 0.6% Ro) with the zone of oil preservation probably only extending to 0.8%, but possibly to 1.2% (Table 5-3).

5. Three morphological forms of bitumen and pyrobitumen were recognised (along with alginite) in the ATP 423P samples (Glikson et al., 1992, Table 5-4). Although their derivation and significance remain obscure, one common form identified as Bitumen B appeared to be the residue of migrated oil.

Pyrobitumen/ Bitumen Type	Characteristics
A	Bitumens exhibiting reflectances the same or close to that of associated alginite
B	Bitumens having a reflectance lower than alginite in the same sample
C	Pyrobitumens having the appearance of discrete bodies and displaying reflectance values significantly higher than those of the associated alginite

Table 5-4. Morphological forms of bitumen and pyrobitumen (from Glikson et al., 1992)

Source rock and oil analyses

Samples from Esso GCD-1, Amoco 83-3 and Amoco 83-4 (including the oil bleed in Amoco 83-4, Figure 3-14b) were analysed at AMDEL to characterise potential source rocks and oils, and learn the possible source of the oil bleed. Two photographs taken in long wavelength blue light fluorescence mode show the oil bleeds. The original bleeds were observed by Amoco on the outside of the core (Dorrins et al., 1983; Plate 12, c). These had been exposed to the atmosphere for seven years when the current photograph was taken. A fresh oil stained surface was also produced when the core was cut at the DME core library for resampling by the author (Plate 12, d). The fresh oil fluorescence is bluish-white indicating a high API gravity, low density oil.

TOC/Rock Eval and gas chromatograph analyses were carried out on the drillhole samples. TOC in the cores ranges from poor to fair (0.27 to 1.61%). The samples for the most part were selected for their presumed organic richness (dark colour). Some dark mudstones analysed however, are obviously iron-rich rather than carbonaceous. Source richness also ranges from poor to fair (0.22 to 2.9 kg/tonne of potential hydrocarbon generation). Tmax and hydrogen index ratios suggest all the samples are immature to marginally mature as also indicated by the reflectivity generated maturities.

The pristane/n-heptadecane and phytane/n-octadecane ratios for the source rock extracts show that samples from 76.8 m and 163.9 m from Esso GCD-1 have similar genetic affinities to the oil bleeds in Amoco 83-4. High Rock Eval production indices (0.21 and 0.25) and extract yields (3343 and 3427 mg/g) also suggest these samples contain migrated hydrocarbons. Other source rock extracts in Amoco 83-3 and 83-4 are not dissimilar to the oil bleeds, but may be more oxidised. The pristane/n-heptadecane versus phytane/n-octadecane plots suggest algal/bacterial sourcing combined with various degrees of oxidation (Watson, 1991). The GC of the saturates from the oil bleed in Amoco 83-4 also shows a broad naphthenic hump which is evidence of biodegradation, possibly during storage (Figure 5-3).

The extracted organic matter from each sample covering many units comprises a mixture of migrated oil and extracted source rock bitumen, probably all of algal affinity. Therefore uniquely characterising one source rock unit which could have produced the Amoco 83-4 oil bleed does not appear possible.

Source rock quality

The carbonaceous unit in Beamesbrook-1, the Train Range Ironstone Member in the Mullera Formation drilled by BHP, and the Doomadgee and Riversleigh Siltstone Formations drilled by AMOCO, are all algal- (and bacterial-) rich over stratigraphic intervals of hundreds of metres. These were source rocks of Middle East proportions in both volume and quality of oil produced, but are overmature today. Most of the data were derived from overmature areas (i.e. post generation), but where source rocks have been sampled in less mature areas they are hydrogen-rich, algal derived, kerogens with excellent oil generation potential, similar to equivalent sequences described by Summons et al., (1988) from the McArthur Basin.

Periods and environments of intense palaeo-biological activity are observable in the rock record of the Proterozoic. The prime oil source was then and has remained throughout much of geologic the Earth's history, a unicellular planktonic alga related to the extant *Botryococcus* (Glikson, et al., 1989). This alga is a lipid-rich hydrocarbon-secreting organism particularly well preserved under euxinic conditions.

Being largely algal derived, the prolific source rock in the northern Mount Isa Basin is characterised as containing Type I and Type II kerogens. This is predominantly a hydrocarbon liquid source as described by Sweeney et al. (1987). Activation energies for oil generation from the various kerogens are given in Tissot et al. (1987). Compared to pure Types II and III kerogens, Type I source rocks have a narrow oil window (see Figures 5-4 and 5-5). Gas generation from Type I source rocks mainly involves late stage cracking (Barker, 1990) as a sulphate-deficient environment is required for bacterial methane production from fresh or brackish water sediments, and a sulphate absent environment in the case of marine deposits (Rice and Claypool, 1981).

Baskin and Peters (1992) described the generation characteristics of sulphur-rich Monterey kerogen (Type IIS). This source rock generates early due to the cleavage of weak sulphur linkages and expulsion by decomposition of bitumens. Although sulphur-rich source rock does not appear to be extensive in the Mount Isa Basin today, the large quantity of sulphide mineralisation and evidence of former gypsum and anhydrite in the basin suggests significant amounts were once present.

Source rock quantity

Some source rocks of the northern Mount Isa and McArthur Basins are characterised by high TOC's of 5% to 10% with estimated migrated petroleum yields (Crick, et al., 1988; Crick, 1988; Crick, 1992) of about 200 000 barrels per hectare. Dorrins et al. (1983) presented TOC plots based on the Amoco stratigraphic drillholes in the northern Mount Isa Basin showing thick intervals of highly carbonaceous rocks.

5.4.3 Generation

The southern part of the northern Mount Isa Basin is demonstrably overmature indicating that all potential oil has been generated in this area of the basin. This generation was probably due to a "normal" geothermal gradient acting on the thick sedimentary pile (partially eroded now), however the asymmetric cross-section of the basin suggests that tectonic pumping of heated brines also may have occurred. Because the units within the basin thicken to the south, maturation was very likely to have been penecontemporaneous or at least closely associated with sedimentation in the deep southern part of the basin, particularly south of the Elizabeth Creek Fault where a thick basin sequence (greater than 10 km) is present.

Thermal evolution

Amoco drillhole 83-4 situated on the northern margin of the Bowthorn Block, contained oil bleeds. These were not extensive, but their very presence suggests that these rocks from the northern part of the basin are within the zone of oil preservation. The alginite reflectance data (0.95 - 1.1%) obtained from the well fully support this conclusion. The alginite reflectance level corresponding to the base of the oil window could be as high as 1.2% (Table 5-3).

More important than the single data point drillhole Amoco 83-4, which is the only documented well within a very wide area, is that the data fit extremely well within a trend supported by data from the other four wells across the basin to the south. The five stratigraphic wells drilled by AMOCO show a clear north-south maturity gradient across the basin. In the south, reflectances of 3.0% to 5.0% are observed. In the central area of the basin reflectances of 1.5% to 2.0% are observed, while at the northern margin reflectances are 0.9% to 1.1%, well within the zone of oil preservation. The stratigraphic hole at the northern margin of the basin (Amoco 83-4) contained both oil bleeds and soluble bitumen veins (not pyrobitumen). Outcrop sampling and uphole reflectance studies (Glikson, 1990) and the 1992 petroleum drillholes, confirmed the widespread low maturities of the shallow northern basin margin.

The seismic data enabled the dramatic south to north thinning of the northern Mount Isa Basin rock packages to be recognised. This probably accounts for the maturation trends across the basin. Overall, the maturation isograds are approximately parallel to the east-northeast axis of the basin and decrease updip in a north-northwest direction. This is similar to the Laramide style basins of Wyoming and Montana where the thermal histories of the basin margins are quite different to that of the central basin areas (Hagen and Surdam, 1989). This trend was exactly that which would be expected for a foreland style basin.

The burial history models which best account for the available data from the northern flank of the basin are presented in Figure 5-6 a and b. The models show that the northern part of the basin sequence has never been deeply buried and potentially may have preserved early generated oil and possibly gas which migrated from the basin depocentre in the south. This series of computer generated "BMOD" burial history and hydrocarbon generation models were produced as a guide to hydrocarbon evolution at the range of prospect sites within the basin. They are handicapped by the lack of detailed age data. (Other constraints on basin subsidence modelling were discussed in Sloss, 1990). Following the 1992 drilling the detailed maturity profiles were found more complex than predicted by the models, as shown previously in Figure 5-2.

By contrast with the Cloncurry Orogen and Riversleigh Fold Zone, the northern flank of the basin remains immature to marginally mature for oil generation today. Extensive thinning of all the major seismic packages on to the northern flank strongly suggests syndepositional growth, or tectonic stability during deposition, with lack of burial and consequent low maturity near the Murphy Inlier, the proposed peripheral bulge. The small area of this zone greatly enhanced the prospectivity of this basin for two reasons. Firstly, shelfal areas in foreland basins around the world are commonly the sites of prolific oil accumulations because they lie in the most favourable migration direction. Secondly, because of the limited areal extent of the prospective area within this basin it was quick, definitive and relatively inexpensive to test.

Finally, information on the nature of hydrocarbons associated with the Arkoma Basin in the USA may be relevant in the case of the McNamara Group. Houseknecht and McGilvery (1990) plus Hathon and Houseknecht (1987) described the supermature vitrinite reflectances from producing gas fields within the Arkoma Basin. Vitrinite reflectances of up to 3.6% were recognised within producing gas fields where early emplaced oil has later been cracked to gas. The interesting possibility is that the fission track record of a late Palaeozoic cooling event in Beamesbrook-1 may relate to late activity within the basin where gas cracking could have occurred during the initial heating (see I.R. Duddy, P.F. Green and S.J. Marshallsea *in* Dunster et al., 1989).

Expulsion or primary migration

Selley (1985) compared the various options to account for primary migration of oil at the threshold of its journey from its original source rock. The possibilities include: expulsion as protopetroleum; expulsion as petroleum in solution dissolved in water, within micelles or as a solution of oil in gas; expulsion as petroleum globules of oil in water; and expulsion as petroleum in a continuous phase.

Because many of the richest source rocks are fine grained claystones, mudstones and siltstones, high temperature expulsion in solution (about 150 to 160°C) associated with compaction and dewatering of clays may be an important mechanism. This mechanism is obviously associated closely with, and dependant upon the subsidence rate and burial history within the basin. Despite the simplicity and obvious possibility of this so called "hot oil" expulsion, serious doubts exist as to whether it occurs at all (Hinch, 1980).

McAulliffe (1980) described an important mechanism of primary migration which leads to the conclusion that the presence of rich source rock facilitates expulsion. This mechanism has been described as the "greasy wick theory". It was proposed that oil and gas are generated in, and flow from, source rock in a three-dimensional organic-matter kerogen network. Oil or gas flowing in this hydrophobic network would not be subject to interfacial forces until it entered the much larger water-filled pores in the reservoir rock. For oil flow to occur oil saturation in the kerogen needs to be from 4 to 20%. Consequently, the rich source rocks in the northern Mount Isa Basin should have been ideal for the production of large quantities of oil.

Although the precise mechanism of primary migration is not known, and indeed more than one may apply in any particular basin, it is known that oil migrates down pressure. This means that the expelled oil moves out of the geopressured source rock, either up or down and into the reservoir. Because of this character, widespread and continuous source rocks make excellent potential seals, and this is the case in the northern Mount Isa Basin.

Apart from source rock quality, rapid burial and maturation is considered to improve expulsion efficiency (Dr D.W. Waples, pers comm., 1989), possibly due to the inhibition of early diagenesis and the high level of the initial petroleum charge. This can be modelled to assess timing of petroleum charge in the context of active and passive generation as shown for the northern Mount Isa Basin in Figure 5-6.

Both the source rock quality and burial history of the rocks of the northern Mount Isa Basin have an important bearing on the primary petroleum migration in the area. From the above discussion it is apparent that the large volumes of high quality source rocks, rapidly buried in the Mount Isa Basin, presented a favourable opportunity for efficient and voluminous oil expulsion.

Fluid inclusion studies

As part of the exploration in ATP 423P, the thermal history was investigated by measuring fluid inclusion homogenisation temperatures in quartz overgrowths, quartz breccia cement and two generations of carbonate fracture and carbonate breccia cement from samples at 121.3 m and 406.4 m in drillhole Amoco 83-4 (Lisk et al., 1991). Homogenisation temperatures were about 102°C for inclusions in quartz overgrowths at both sample depths and about 125°C for late carbonate cemented fractures and breccia porosity at both depths.

Lisk et al. (1991) reported yellow fluorescing and blue fluorescing liquid hydrocarbon inclusions (under violet and ultraviolet excitation) from carbonate fracture cement from the Doomadgee Formation at 121.3 m in the Amoco 83-4 borehole from the Lawn Hill Platform. Probable methane-bearing gas-rich inclusions occur in all diagenetic cements in the 121.3 m sample, and are abundant in the sample of Walford Dolomite from 406.4 m. The presence of methane inclusions suggest there was an immiscible methane phase present during crystallisation of diagenetic mineral cements and that the homogenisation temperatures are the temperatures of cementation. No correction for palaeodepth was required. Similar temperatures measured on samples from both depths indicate that the fracture and breccia zone was isothermal during cementation and that over a period of 40 Ma the temperatures increased from about 102°C (isothermal) to about 125-135°C (isothermal).

Consistency between BMOD calculated maturity and measured maturity data in Amoco 83-4 suggests that the temperatures of cementation are maximum palaeotemperatures near Amoco 83-4 and that cementation occurred when the rocks were at maximum burial depth (confirmed by the presence of liquid oil in vugs in Amoco 83-4). This maximum burial was probably between 1400 Ma and 1000 Ma following completion of deposition within the basin. Hydrocarbon migration is thought to have mostly occurred by this time.

The rocks in Amoco 83-4 had some porosity due to fracturing and brecciation, and were possibly a migration pathway for hydrocarbons and carrier fluids that originated from a range of depths and source rock maturities in the depocentre of the Mount Isa Basin. The fracture and breccia zone probably acted to focus fluids flowing out of the basin. Since the upper Fickling Group rocks contain oil prone sapropelic organic matter the methane in the inclusions probably had a thermogenic origin. The migration sequence observed in the mineral cements in Amoco 83-4 may differ from the sequence of generation of hydrocarbon fluids in the basin. Late-formed thermogenic methane may have displaced liquid hydrocarbons from a deeper reservoir causing the liquids to appear late in the migration sequence.

Lisk et al. (1991) reported that the diagenetic sequence in Amoco 83-4 appears to have been quartz followed by carbonate breccia cement and finally vein carbonate. In sample 406.4 m the euhedral quartz contains aqueous, liquid hydrocarbon and gas-rich inclusions, while the quartz overgrowths exhibit aqueous and abundant gas-rich inclusions. The carbonate breccia cement held abundant gas rich inclusions. In the sample from 121.3 m the quartz overgrowths contained gas-rich inclusions while the carbonate breccia cements were both liquid hydrocarbon- (white, yellow, white-blue, yellow-green fluorescence) and gas-rich. The vein carbonate contained liquid hydrocarbon-rich inclusions (white-blue, yellow-green fluorescence).

Brine compositions in the inclusions studied by Lisk et al. (1991) ranged from 10 to 30wt% NaCl equivalents.

Lisk et al. (1991) drew two significant conclusions from the above data. They were:

Firstly, the similarity in homogenisation temperatures between the two samples suggested a negligible temperature gradient due to heat transfer being dominated by fluid flow.

Secondly, the range of fluorescence colours suggested more than one source for the oil inclusions in the sample at 121.3 m. Generally it appeared that a range of liquid and gaseous hydrocarbons plus aqueous fluids had been entrapped throughout diagenetic cementation in the basin. This also suggested a range of maturity levels for the expelled oil and gas during diagenetic cementation.

Additionally, the fluid inclusion evidence suggested there was significant methane generation within the depocentre of the Mount Isa Basin sequence and this was an important factor in assessing the hydrocarbon charge of target reservoir traps. Gas caps, oil legs, or gas filled reservoirs were possible. Fluid inclusion studies and burial history models each showed various pulses of generation occurred associated with deposition.

The work of Lisk et al. (1991) served both to confirm and expand upon the basin model in that while the northern basin margin was still obviously prospective for preserved hydrocarbons, the vertical heat transfer in Amoco 83-4 suggested dynamic and potentially destructive hot brine migration conditions.

5.4.4 Seal

Seals are critical to hydrocarbon entrapment. Downey (1984) described the characteristics of effective seals. Many natural, pre-diagenetic seals are present throughout the Mount Isa Basin. The several excellent quality source rocks observed in outcrop and in the drillholes would each make good quality seals. The major seal tested during the drilling of the play in the basin, however was the thick (over 1000 m) turbidite-deposited Riversleigh Siltstone.

The carbonaceous unit immediately below Horizon C at 1215 m in Beamesbrook-1 had the potential to be an excellent source and seal. On the seismic event mapping it was continuous throughout the area of the survey and was intersected in each 1992 drillholes. The inference being that widespread continuity ensured favourable long distance migration throughout the basin in underlying sandstones.

5.4.5 Reservoir

Several reservoirs and potential reservoirs occur within the northern Mount Isa Basin. The best are late-developed reservoirs produced by secondary enhancement of porosity probably from leaching of cryptalgal structures in the Walford Dolomite. Esso GCD-1, a mineral bore in the area, currently flows artesian water from the Walford Dolomite.

Possible palaeokarst development was recognised in the Walford Dolomite during the inspection of the core from drillhole Esso GCD-1. Pelechaty and James (1991) described dolomitised Mesoproterozoic calcretes of the Kanuyak Formation from Bathurst Inlet, Northwest Territories, Canada. They considered the Kanuyak Formation profiles to exhibit many attributes similar to duricrusts of Phanerozoic and Recent ages (cracks, cements, accretionary grains and deformation structures) except for those associated with plant and animal activity (rhizoconcretions, root moldic porosity etc.). The study concluded that the microbiota most likely also contributed to calcretisation. A similar mechanism is possible for the Walford Dolomite. Muir (1983) recognised a Proterozoic calcrete in the Amos Formation of the McArthur Group in the McArthur Basin.

As with the McArthur Basin, the Mount Isa Basin sequences lack widespread primary reservoir units. Despite this, maturation within the basin was undoubtedly early, and almost certainly predates the widespread though erratic diagenesis now observed. Because of this early maturation, early migration and entrapment of oil can be expected to have produced oil filled structures, where the presence of oil could have prevented the diagenetic occlusion of porosity within the trap.

Early clastic potential reservoir facies were intersected in several upholes, principally as turbidite channel sands, and these could have been capable of forming oil reservoirs where early emplaced oil had inhibited occlusion of porosity by diagenesis (using the principles of Wilson, 1977; O'Brien and Lerche, 1986; Cant 1983). This is the situation in the Arkoma Basin where gas production is derived from early trapped oil cracked to gas reservoired in structures where primary porosity has been retained (Houseknecht and McGilvery, 1990).

Fracture induced porosity (similar to that in the Amadeus Basin) may also have been present in some fault crush zones evident on the seismic sections. Minor late movement on the Egilabria structure (post-Mesozoic) also possibly created some secondary fracture porosity capable of acting as a gas reservoir. Lorenz et al. (1991) have described a load-parallel extension fracture mechanism which accounts for the common presence of regional fractures in subsurface reservoirs in flat-lying strata. Similar types of fractures could be present in the northern Mount Isa Basin.

The occurrence of dolomitisation and possible subsequent dedolomitisation in carbonates is difficult to predict. These processes could have enhanced potential carbonate reservoirs in some places in the Mount Isa Basin.

Volcanic input which commonly breaks down early to clays creating poor reservoir conditions appears to be confined to the basal volcanic rocks (which have some reservoir potential in sandstones and carbonates) and the Lawn Hill Formation. In summary, outcrop evidence shows that abundant potential primary reservoirs were deposited in the basin, but their geographic and lithostratigraphic distribution within the Bowthorn Block is not yet fully defined.

Seismic data from ATP 423P, and field observations by Esso and Amoco geologists clearly indicate the presence of many important and widespread unconformities. Billington (1991b) described highly weathered Mt Les Siltstone underlying fresh Doomadgee Formation along the northern margin of the Mount Isa Basin in the Northern Territory. Up to 50 metres of erosion was observed in places at the top of the Mount Les Siltstone. Major unconformities such as those seen on the Bowthorn Block seismic sections would have had significant reservoir potential where the large karstic style void space present developed soon after deposition, for example in shallow carbonate environments and also could be enhanced by secondary dolomitisation associated with brine movement. The large storage capacity of this kind of unconformity reservoir would possibly have been sufficient to prevent diagenetic cementation.

Thin section petrography

A range of drillhole samples were sectioned in an attempt to unravel the diagenetic sequence and characterise any existing porosity (Moultrie, 1991b).

Two Mullera Formation sandstone samples from BHP drillhole DDA-130 located near the southern margin of the South Nicholson Group exhibited no porosity. In these samples quartz overgrowths occluded all pore spaces.

Walford Dolomite outcrop samples showed the best estimated visible porosity with 15% to 20% in oolitic and oncolitic outcrop samples (Plate 12, h). Much of this may be modern however. Porosity occlusion in the Walford Dolomite outcrop samples is due to dolomite and silica cementation.

Walford Dolomite core samples were also observed to contain both silica and dolomite cements with three silica cement phases (checkerboard, isopachous - a thin uniform rind around the grain exterior, and megaquartz). In these samples the silica has replaced dolomite. Late dolomite (?calcite) cross-cutting veins are also present. A sample of this late stage, coarse grained, crystalline, vein dolomite from 557 m in Amoco 83-5 was analysed by XRD at QUT and found to be pure, simple dolomite. This dolomite generation may have occluded porosity elsewhere.

Beamesbrook-1 chip samples exhibit very low porosity, but are all natural low porosity rocks i.e. mudstones and siltstones. Both silica and dolomite cements (with fluid inclusions) are present, but there is no evidence to suggest an order of cementation.

Desert Creek-1, Argyle Creek-1 and Egilabria-1 samples from the 1992 drilling produced similar results. Even natural high porosity lithotypes such as the coarse sandstones and oolitic dolomites were occluded with silica and dolomite cements.

Provenance

The only volcaniclastic rocks in the platform and foreland sequences of the northern Mount Isa Basin were observed within the Lawn Hill Formation near Century. These are not volumetrically significant, consistent with the peripheral foreland basin interpretation, and so do not make up any serious threat to the primary reservoir potential of the basin. Because province in peripheral foreland basins may be both from the orogenic belt or the cratonward side of the basin, the lack of widespread volcanism in this type of basin allows excellent reservoir systems to develop. In the northern Mount Isa Basin, the seismic data suggest the predominant source of sediment supply was from the orogen to the south while the preserved basin lithostratigraphy indicates little volcanic input.

Clastic reservoirs

In the field today almost all of the surface outcrop has undergone extensive silicification and diagenetic alteration (not necessarily produced by weathering) and this also appears to be the situation in most of the shallow drillholes in the basin. It therefore appears, that outside an intact hydrocarbon trap, the preservation of porosity is very unlikely.

Because silica and carbonate cements have largely occluded porosity throughout the Mount Isa Basin today, the only predictable reservoirs may be due to fracturing. These reservoirs could easily occur in such a brittle sequence, however they are not the target of choice in a grass roots exploration prospect.

The other possible reservoirs, particularly in the clastic foreland sequence are major unconformities which may have survived diagenesis through gross void capacity. If these are present they should be conformable with the general sequence and therefore form traps at the same locations as any pre-diagenetic structure and so this concept was tested during the 1992 drilling campaign with negative results.

Because generation, migration and entrapment were probably early, they most probably predated lithification and therefore good reservoir units could be preserved. These can be predicted from the known stratigraphy of the basin. Once filled by oil, diagenetic waters would have been unable to penetrate the reservoir, resulting in an oil filled structure encapsulated in an otherwise tight reservoir formation. This precise situation has been described in many oil fields. It means that the lack of porosity and permeability in the shallow mineral stratigraphic drilling and outcrop geology can be considered a poor guide to the petroleum reservoir potential of the basin. In the McArthur Basin, Womer (1986) described the diagenetic sequence and recognised the interfering effect of hydrocarbons.

Carbonate reservoirs

Diagenesis

The major potential reservoir in the northern Mount Isa Basin is the carbonate sequence composed of the Walford Dolomite and its equivalents, the Lady Loretta, Esperanza and Paradise Creek Formations. Very little dolomite forms in modern environments and this is possibly true of conditions in the Proterozoic although the direct precipitation of dolomite from seawater may have been possible in association with highly reducing Proterozoic environments (Dr. D. Taylor, pers. comm., 1991). The presence of dissolved sulphate in seawater inhibits the direct precipitation of dolomite in preference to calcite. Certainly the high ionic strength of seawater and fast carbonate precipitation rates combined with hydration of Mg^{2+} and low CO_3^{2-} activity all favour calcite precipitation.

Dolomitisation is a carbonate stabilisation processes that requires two basic elements (Sneider, 1986). These conditions are:

1. A physical-chemical environment in which dolomite is the stable carbonate mineral.

2. A means of transporting magnesium bearing fluid to the site of dolomitisation.

As a result, the modern formation of dolomite is interpreted on the basis of several models primarily related to calcite alteration. Dolostones are observed to have multiple origins which are commonly multi-staged, but they can be grouped into three main types; syngenetic, diagenetic and epigenetic (James, 1991). Syngenetic dolomite is finely crystalline and forms early associated with tidal flats and ephemeral lakes. Diagenetic dolomites form in sabkha environments and both replaces aragonite fossils and infills intergranular porosity. Epigenetic dolomites form in modern reefs by microscopic replacement and growth into voids. In foreland basins, magnesium may be stripped out of the hot deep basin sediments to dolomitise the outflow areas along the basin margin. This commonly forms in karst breccias where burial calcite precipitation is expected. Fluids with elemental sulphur or hydrogen sulphide can excavate large caverns producing hot water karsts. At foreland basin margins both hydrocarbon and lead/zinc entrapment can occur in such areas (Professor N.P. James, pers. comm., 1991).

In the northern Mount Isa Basin both karst surfaces and sink holes have been recognised from drillholes and outcrop respectively (drillhole Esso GCD-1 and AGSO 1:100 000 geological mapping). Late developed reservoirs as secondary enhancement of porosity by leaching of cryptalgal fabrics and possible palaeokarst development, have been observed in the Walford Dolomite. Esso

GCD-1 is a flowing artesian bore producing fresh water from the Walford Dolomite. Under relatively low pH conditions (less than 8), silicification resulting in the dissolution of calcite and the precipitation of quartz occurs. If the migrating waters had a pH of greater than 9, i.e. relatively alkaline, then precipitation of calcite and dissolution of silica is favoured. Silicification of the carbonates in the northern Mount Isa Basin is common.

Dolomitisation, resulting in the dissolution of silica and the precipitation of high magnesian calcite, is favoured by alkaline conditions such as the presence of sulphate evaporites. Warren (1989) stated that evaporite diagenesis can release large quantities of magnesium-rich brine and so form sucrosic dolomite, an excellent potential reservoir. Evidence of the presence of alkali evaporites is sporadic throughout the northern Mount Isa Basin, but is present within the Walford Dolomite Formation near Walford Creek. While sucrosic dolomite has been observed in cored drillholes in the northern Mount Isa Basin, the relationship with evaporite-derived brines has not been confirmed. Lead/zinc mineralisation has been discovered at Walford Creek. The former existence of evaporites in the area may have controlled both selective silicification within formations such as the Walford Dolomite and constituted a prime control on lead/zinc mineralisation in the overlying Mount Les Siltstone.

Continuity

Depositional environments in carbonate systems exhibit both heterogeneity and significant complexity. Carbonate diagenesis is pervasive and relatively rapid with many subtle physiochemical controls. Carbonate reservoirs are therefore not unexpectedly characterised by great variation in porosity and permeability at many scales. Warren (1990a and b) reviewed this problem.

The carbonates of the northern Mount Isa Basin are typically variable both along strike and basinward. Many facies were recognised including oolitic banks which would have had excellent primary porosity and are porous in outcrop today, but are occluded in the sub-surface (see Walford Dolomite described in Section 3.7.2). Such porosity is usually occluded very quickly during early diagenesis, but it is a good target for secondary porosity. Because of the age of the rocks and complex depositional subsidence and post-depositional deformation, the carbonates exhibit additional complex diagenetic overprinting observable from both outcrop and drillhole data. All of this has resulted in quite intricate variability.

Subaerial Exposure of Carbonates

In many basins, past subaerial exposure of carbonates has commonly led to the development of laterally extensive porosity and permeability either in pervasive secondary coarsely crystalline (sucrosic) dolomite horizons or early collapse breccias. After subsequent burial, a porous zone can provide a suitable trap for hydrocarbons or become the focus of stratiform Mississippi Valley type mineralisation. Solution collapse brecciation and coarsely crystalline dolomite have both been reported in the Walford Dolomite. The widespread shallow water to supratidal conditions under which the Walford Dolomite was deposited lend themselves to potential multiple exposure events. The stacked shallowing-up cycles seen in core from the Amoco 83-4 drillhole probably represent local changes in the rate of subsidence relative to deposition. Widespread eustatic sea level changes may be responsible for the solution collapse mapped in outcrop of the Walford Dolomite (AGSO Hedleys Creek 1:100 000 Sheet). The mineralisation within the Mount Les Siltstone at Lead Hill (up to 10% lead) was reported to be a collapse breccia style deposit (Grimes and Sweet, 1979), but field inspection revealed it to be a mineral vein infilling of vertical and horizontal joints and fractures.

The first step in predicting permeability associated with subaerial exposure is understanding the process of dolomitisation. The timing of halite dissolution is a key factor in determining which model(s) of dolomitisation apply to the Walford Dolomite in different parts of the basin. The importance of halite and other evaporites within the Walford Dolomite has probably been underestimated since almost all work has concentrated on the flanks of the basin, while (by analogy with other basins) the thickest development of evaporites should occur in the depocentre. The conventional model for evaporites predicts displacive halite hoppers grown by authigenic recrystallisation beneath a subaerially exposed sabkha on the flanks of the basin. This was indeed observed in the Walford Dolomite. Much more extensive bedded halite (characterised by aligned chevrons) and possibly sulphate evaporites can be inferred to have been deposited in the centre of such a basin (Warren, 1990a). These evaporites could have provided the highly saline (commonly Mg-rich) brines necessary for both dolomitisation and metal transport. Both vadose and phreatic diagenesis can be involved in mineralisation of subaerially exposed carbonates, although the action of meteoric waters in the upper palaeo-phreatic zone is cited more usually. In the Walford Dolomite, this may be complicated by fluctuations in sea level, uplift and diagenetic changes to carrier beds. The most intensive dolomitisation (producing sucrosic dolomite) can be expected to have occurred landward of the sabkha. Bedded halite (or other evaporites) often retain their integrity as seals even after considerable tectonic deformation.

With further work on the Mount Isa Basin, the sedimentology and diagenesis will be better understood, and it may be possible to tie subaerial exposure surfaces caused by eustatic sea level changes to individual seismic reflectors. These could then be mapped over their entire distribution. Such reflectors should also be closely scrutinised for evidence of direct hydrocarbon indicators.

Results

Field work in the northern Mount Isa Basin produced two very significant observations regarding the reservoir potential of the McNamara and Fickling

Groups. Firstly, an artesian flow was observed from an Esso mineral drillhole spudded into Doomadgee Formation, with the flow probably coming from the Walford Dolomite level (not reported in the well completion report). Before this observation, the only reported artesian aquifer flow was in drillhole Amoco 83-3 from the Constance Sandstone. Western Mining drilling at Walford Creek during 1992 also intersected artesian flows in the area. Secondly, widespread and potentially thick zones of halite hopper accumulation within the Walford Dolomite were observed. The original salt may have been leached during brine movement early in the history of the basin resulting in major porosity development in the form of the halite cast zones observable today. If they were leached but unsilicified at depth, the cauliflower chert evaporite zones, also observed within parts of the Walford Dolomite, were potential reservoirs.

The following list summarises the observed features of the northern Mount Isa Basin which appeared to offer the best chance for petroleum accumulation and reservoir production.

1. The presence of a flowing artesian bore in the Walford Dolomite and probable fracture zones in some other units are a positive reservoir indication.

2. The existence of halite casts, evaporites, pseudomorphs, breccia zones and fresh dolostone in places, all enhance the possible reservoir potential of the Walford Dolomite as reservoir resulting from similar features in younger basins is common.

3. Observed minor late movement on the Egilabria structure (post-Mesozoic) may have created some secondary fracture porosity suitable for gas production (late movement can also result in leakage).

4. The oils observed in the basin are light and mobile which would enhance their production potential (or the production of gas or condensate) in a tight reservoir situation.

The three wells drilled by Comalco during 1992 did not locate any preserved reservoir in the basin and this result significantly downgrades the potential for preserved petroleum in the basin today. Bloch (1991) recognised that empirical predictions of porosity and permeability which are basin or even play specific provide the best guide. On this basis, reservoirs other than fracture systems are unlikely to be found in the Mount Isa Basin.

5.4.6 Migration

Primary migration (see section on expulsion under generation)

Secondary migration

Bethke (1990) described at least seven factors which interplay to control groundwater movement and hydrocarbon migration in basins with foreland architecture like the Mount Isa Basin. They are:

1. Topography -- In steady state flow regimes, undulating present day topography can impose complex near surface flow variations locally. It is therefore imperative to understand the topography at the time of oil migration, as well as present geomorphology. In the Mount Isa Basin, Andean scale mountains probably existed in vicinity of Mount Isa and the area to the south during the time of oil generation.

2. Sediment compaction -- As sediments compact, they transfer some of their weight to the pore fluid. As a result fluids are driven towards the surface or into less rapidly compacting sediments. Sediment compaction can lead to the development of overpressure. Overpressure results from rapid burial of fine grained sediments, which, being unable to dewater quickly, require the fluid to support the load of the sedimentary pile rather than the rock matrix. Overpressure is function of sediment type, permeability, sedimentation rate (a sedimentation rate of at least 1-10 mm/yr is required to overpressure shales), rate of subsidence, clay composition, lateral compression, sea level change, and heat flow, all of which could have applied to the Mount Isa Basin, particularly in the foreland phase. Oil migration usually occurs along the top of the overpressure zones. Both overpressure, and its release, will re-migrate oil. The effects of sediment compaction are usually subordinate to those of topography.

3. Migration of the depocentre -- Both during hydrocarbon generation and subsequent to it, the location of the depocentre can affect hydrocarbon migration. In the case of the Mount Isa Basin progressive cannibalisation of the

basin resulting from foreland orogenesis probably squeezed fluids northward in combination with the hydrodynamic flow.

4. Sea level fluctuations -- Greater flushing will occur at sea level low stands.

5. Erosion of overlying sediments -- This commonly imposes local variations.

6. Lateral and temporal permeability variations of seals -- This is common. True large-scale aquicludes are unknown in nature. All seals pass fluid to some degree and are really aquitards, but the rate of fluid loss may be very small.

7. Pinching out of a basal reservoir (aquifer) produces local discharge and recharge areas superimposed on the regional flow regime.

Points 4 to 7 would all have affected the northern Mount Isa Basin, but the lack of data means that the precise influence of each factor is difficult to assess. Contrary to popular opinion, most groundwater recharge is believed to occur by seepage down through confining layers rather than directly into the outcrop of the aquifer (Dr. C. Bethke, pers. comm., 1990). Therefore although a relatively fine-grained flysch sequence was deposited during the basal foreland phase of the northern Mount Isa Basin, significant recharge of the passive margin phase probably occurred.

Mechanisms of oil migration

Bethke (1990) described three types of drive mechanism:

1. Hydrodynamic (downward or upward movement of groundwater flushing hydrocarbons by processes such as the ones described above).
2. Buoyant (oil droplets rising through water).
3. Capillary (oil preferentially entering fractures and pores and displacing water - a surface tension-like effect - can move oil in any direction including downward).

All three types of drive will be operational in any one fluid system at one time, but any one particular drive may be the major contributing factor to oil migration. For instance, depending on the velocity of the hydrodynamic drive, oil droplets rising vertically may or may not be carried laterally. Various basins exhibit different kinds of drive. Because Eromanga Basin structures are not flushed, buoyant drive can be inferred to be predominant in similar situations of low ground water flow. The Illinois Basin is cited as an example of long distance (in excess of 300 km) oil migration involving the interplay of all three forms of drive. (Several relevant papers on the Illinois Basin were collected by Leighton et al., 1991). Oil sourced from Mesozoic rocks is believed to move down by capillary drive to underlying tight Devonian carbonates which act as a carrier bed at the porous permeable unconformity surface. Hydrodynamic drive carries the oil through fractures and low porosity and permeability intervals of carbonate before rising by both buoyant and hydrodynamic drive into basal Mesozoic reservoirs hundreds of kilometres away. A similar powerful lateral migration style is envisaged for the Mount Isa and McArthur Basins which are quite similar to the Arkoma-Illinois analogue.

Velocity, efficiency and direction of migration

In terms of the velocity of hydrocarbon migration, the best carrier bed is not necessarily the stratigraphic interval with the best porosity and permeability. For optimum efficiency of oil migration, as little as possible of the carrier bed should be oil-saturated. Thus a low permeability heterogenous sandstone or a fractured shale can be a more efficient carrier bed than a clean sandstone. This applies only to the speed with which hydrocarbons migrate. A clean sandstone could move a greater volume of hydrocarbons although more hydrocarbons would remain in the rock as irreducible oil saturation (Bethke, 1990). Because it is envisaged that large quantities of oil have been produced and migrated in the Mount Isa Basin it is considered that high porosity-permeability systems probably acted as the primary migration pathways.

It is generally accepted that fault planes do not act as deep migration conduits unless the fluid pressure is close to the overburden pressure or a permeable gouge is formed. In the Mount Isa Basin today, the rocks are brittle and highly lithified, an ideal situation to form permeable fault gouges. On the other hand, continuous permeable beds across faults can be very important migration pathways (Nybakken, 1991) and this situation is bound to have occurred to some extent throughout the history of the Mount Isa Basin.

The exposed northern Mount Isa Basin dips regionally to the south and within the southern basin both strike-slip and thrust faults are common. Because the rock packages in the Bowthorn Block are progressively thicker southward, the northern margin (the Murphy Inlier) obviously existed during basin subsidence. It is therefore clear that most of oil generated in the basin would have migrated north. As loading of the sedimentary pile initiated maturation, it can be interpreted that migration was penecontemporaneous with later basin deposition.

In the Mount Isa Basin, brine migrations are believed to have been triggered by orogenic movements in the thrust belt which progressively migrated from south to north. The primary driving force of migration is considered to have resulted from topographic variations, specifically the Andean scale mountain belt which is probably enabled the development of an artesian head during basin subsidence (compare this to Arkoma Basin sections, e.g. Blythe et al., 1988). Geopressures, due to movement of the thrust belt were probably present during compaction of the Mount Isa Basin, but these dissipate with time.

One important aspect of secondary migration in foreland basins relates to thermal degradation by hot brine during transport. In this respect, the plumbing system and its evolution must be well defined to enhance prospectivity. Areas where later hydrocarbon degradation by brines may have occurred can therefore be avoided. Even with the 1992 drilling results, the data set from the northern Mount Isa Basin remained insufficient to reconstruct the details of the plumbing system and to evaluate its evolution. The alginite reflectances from the Beamesbrook-1 and Argyle Creek-1 wells in the Bowthorn Block suggest active and hot brine moved through the sites of these wells (Figure 5-2).

5.4.7 Structure - The trap

Two obvious phases of structuring occurred throughout the Bowthorn Block of the northern Mount Isa Basin. These were directly associated with the basin forming tectonic regimes. The first generation of faults were produced in a thick-skin extensional growth fault system, typical of rifts in many parts of the world. No obvious thin-skin compactional faults were observed in either the rift or passive margin phases within the Bowthorn Block. The second generation of faulting during and following the foreland phase of Mount Isa Basin evolution included thin-skin tear faults, thrusts and decollement buckles.

Thick-skin wrench faults appear to have been formed relatively late after the two main phases described above. These were possibly associated with east-west compression. All of this deformation has resulted in the existence of a wide variety of structural traps at various times during the deposition and evolution of the Mount Isa Basin.

Structural traps

Several large structures were identified, gridded and defined on the seismic lines shot in the Bowthorn Block. In total, three reliable structural tests were drilled in the basin. These were Desert Creek-1, Argyle Creek-1 and Egilabria-1. Potential reserves for the structures drilled in 1992, based on nominal downhole parameters, are presented in Figure 5-7 and Table 5-5. The level of potential reserves determined represented sufficient upside potential to justify the exploration program in the basin. Reserves for Beamesbrook-1 drilled in 1988 are not included as this was a speculative stratigraphic well based on poor seismic control.

The structures drilled in the Bowthorn Block of the northern Mount Isa Basin were formed shortly after foreland deposition as thrust reactivation of down-to-the-north normal faults. The structures are obviously Pre-Mesozoic, but post-date the deposition within the basin. Because the compressional faults are reactivation features closely aligned and continuous with older structural breaks observed on the seismic sections, it can be reliably suggested that the major fault zones are breaks of long standing within the basin. Figure 5-8 shows a range of possibilities for the development of structural traps within the basin. Nybakken (1991) discussed the nature of sealing fault traps and the need for a large mature data set to evaluate sealing by faults. Insufficient data are available in the Mount Isa Basin to determine individual fault fluid transmission characteristics.

To the south of the Elizabeth Creek Thrust Zone, the marked angular unconformity at the base of the South Nicholson Group enables recognition of the structures within the south of the basin before South Nicholson Group deposition. Equivalent structures north of the Elizabeth Creek Thrust would have closely post-dated the cessation of deposition in the basin. The gridded structures in the Bowthorn Block tested during the 1992 drilling were therefore highly favourable for petroleum entrapment.

Drill Target Horizons	Area km^2	Vertical Closure m	Conical Rock Volume MM m^3	Recoverable Oil		Recoverable Gas (38 MJ m^3)		
				MM m^3	MMB	B m-3	BCF	PJ
Egilabria-1 Z	3	48	48	0.4	3	0.9	31	33
A	6	124	248	2.2	14	4.5	159	171
B	3	175	175	1.6	10	3.2	112	121
C	4.8	187.5	300	2.7	17	5.4	192	207
D	3	50	50	0.5	3	0.9	32	34
Desert Creek-1 C	24	175	1400	12.7	80	25.4	897	965
D	10	150	500	4.5	28	9.1	320	345
D1	21	150	1050	9.5	60	19.1	673	724
Argyle Creek-1 D	12	175	700	6.3	40	12.7	449	483
D1	16.3	200	1083	9.8	62	19.7	694	747
Fault Independent component of Egilabria-1* Z	3	23	23	0.2	1	0.4	15	16
A	6	60	120	1.1	7	2.2	77	83
B	3	60	60	0.5	3	1.1	38	41
C	4.8	60	96	0.9	5	1.7	62	66

* Minimum closure to fault independent spill point

Parameters	Porosity	Recovery	Oil/Gas Saturation	Net/Gross Pay	Formation Volume Factor Expansion/ Shrinkage*	In-situ to surface factor
Oil	0.15	0.3	0.6	0.5	0.67	0.009045
Gas	0.15	0.8	0.9	0.5	336	18.144

* Assumes 4000 psi, 2000 m, 9.8 ppg

Table 5-5. Calculated hydrocarbon reserves and estimated reservoir parameters for the 1992 petroleum wells assuming full to spill point reservoirs

Stratigraphic traps

Many potential stratigraphic traps exist within the northern Mount Isa Basin. These are displayed on the various regional seismic sections (Figure 3-29 and Enclosure 6). The greatest trap potential was observed on seismic lines such as 91BN-08 where the platform carbonate sequence was truncated by the basal foredeep unconformity.

Because stratigraphic traps are difficult to define in three dimensions and for the most part require characterisation of both topseal and baseseal to produce a play, initial testing of the northern Mount Isa Basin was confined to the pure structural tests described above with the emphasis being on gaining reliable information on hydrocarbon accumulation in the area. The concept of stratigraphic entrapment (which invariably produces the earliest syndepositional traps) within the basin remains valid and certainly provided enough long-term potential to encourage the initial structural tests.

5.4.8 Timing of generation and migration

In rapidly subsiding basins such as the foreland phase of the Mount Isa Basin, the timing and close association of generation, migration and structural deformation within the northern Mount Isa Basin is very favourable for the production of petroleum filled structures. Timing of silicification within the basin necessarily post-dated petroleum migration because generation in such a thick basin sequence was early. Minor oil and gas generation probably occurred during the rift and drift phases, but the best source rock deposition, with extensive oil and gas generation appears to have occurred during the foreland deposition. Once petroleum has filled structures, early diagenesis can shield the original oil filled porosity resulting in final diagenetic entrapment at the oil-water contact. This may be a mechanism to explain the generation of the possible seismic flat spots on the 1989 seismic lines which were tested by drillhole Egilabria-1 (see Section 5.4.10, Direct hydrocarbon indications).

Secondary migration due to leakage as shown in Figure 5-8, is an important consideration in grass roots exploration like that undertaken in the Mount Isa Basin. Fortunately, from the point of view of migrated hydrocarbon entrapment in the basin, the presence of early faults related to the rift phase deposition ensured that some traps would have formed early.

5.4.9 Preservation

Preservation is the key to the northern Mount Isa Basin's potential for commercially viable trapped hydrocarbons. Preservation potential in the basin appeared to be quite good prior to the 1992 drilling. The sequence is close to its original attitude and is not pervasively faulted. No intrusions were identified.

There appeared (before the 1992 drilling) that there were three main arguments for hydrocarbon preservation in the Bowthorn Block of the northern Mount Isa Basin:

1. The basin is not too old because live oil exists in many formations today.

2. There is no evidence of fault or unconformity breaching of traps, but faults are common, and the pervasive silicification indicates the rocks have undergone brittle failure. This could have led to significant leakage of the kind that has been described by Downey (1984), but the seismic data suggests the potential hydrocarbon traps were structurally intact.

3. It was considered that the hot brines associated with migration and metal deposition within the basin were unlikely to have degraded early emplaced hydrocarbons. This was a significant risk particularly in shallow water carbonates which can form extensive aquifer systems (Professor G. D. Klein personal communication, 1992). Consequently, hydrocarbons trapped in less extensive turbidite channel sandstone reservoirs were considered less likely to have been degraded by migrating metal-rich brines common in foreland basin systems.

This last risk is believed to be the key factor resulting in the drilling program not discovering any commercial hydrocarbons (Section 5.5, Results and perspectives).

Age

Provided immaturity or oil window maturities are maintained within a hydrocarbon-filled trap, degradation should not occur, because the kinetic conditions for such reactions will simply not be met. Even time-temperature index models suggest negligible degrading of oil occurs during extensive periods when low geothermal conditions prevail. Diagenesis and porosity occlusion under low maturity conditions should enhance preservation potential.

Krooss et al. (1992) quantified gas diffusion through cap rocks of natural gas reservoirs. Using their formula, diffusion rates for the northern Mount Isa Basin have been calculated for various caprock thicknesses. Figure 5-9 graphs the time taken for gas reservoir depletion given a set of typical conditions. While these curves represent theoretical maxima, depletion may be slowed by changes in reservoir conditions and recharge. Embrittlement of clastic caprocks through diagenesis could be expected to enhance gas losses.

Alteration

Fluid inclusions in diagenetic cements, from drillholes on the northern flank of the basin exhibit a range of fluorescence colours (Lisk et al., 1991). This suggests a range of maturity levels for the oil and gas trapped during diagenetic cementation.

Based on the Type I and Type II algal and bacterial organic matter in the northern Mount Isa Basin, oil should survive through to alginite reflectance level of about 1.2%. Wet condensate should survive to a reflectance level of about 2.0% (Table 5-3). These conclusions are based on the conditions which governed preservation in the nearby McArthur Basin of the Northern Territory. Small quantities of live Proterozoic oil have been recovered in several areas of the McArthur Basin.

Hunt (1975) reviewed the geochemical limitations for hydrocarbons. Although oil is thermodynamically unstable in sedimentary basins and exists only because the kinetics of conversion are slow, methane is stable in an inert dry reservoir to 550°C (Takach et al., 1987). Therefore provided trap integrity was maintained, gas field preservation should be theoretically possible in Proterozoic sequences. Certainly, commercial gas of Palaeozoic age is produced from depths in excesses of 7500 m in the Anadarko Basin of Oklahoma (Cardott and Lambert, 1985).

Areas of oil preservation and thermally overmature source rocks appeared to be mutually exclusive before the 1992 drilling. Although significant hot brine movement is now believed to have occurred throughout the northern Mount Isa Basin, this basin margin exhibits oil window maturites at some stratigraphic levels in some areas and these remain as small prospective areas of preservation.

Phanerozoic resetting of fission tracks in apatite has been documented for Beamesbrook-1 samples (see I.R. Duddy, P.F. Green and S.J. Marshallsea *in* Dunster et al., 1989). The tracks suggested the possibility of late generation within the Mount Isa Basin, but also that water washing and deasphalting of existing trapped hydrocarbons may have occurred.

Because of the very narrow, shallow hydrocarbon preservation window at the northern margin of the Bowthorn Block, biodegradation could have been a potential problem. The many oil indications in shallow upholes however, suggests that biological agents have great difficulty penetrating the well lithified basin strata. The numerous well lithified seals throughout the basin probably preclude biological activity in most potential reservoirs.

5.4.10 Direct hydrocarbon indications

A range of oil and gas indications exist throughout the northern Mount Isa Basin. Oil bleeds in core (Plate 12, c) were first ambiguously reported by Amoco (Dorrins et al., 1983). Gas shows were reported in an Amoco mineral drillhole GRQ 81-2 at the northern Mount Isa Basin margin (Wilkins, 1982). Many oil bleeds were observed in uphole chip samples and even outcrop samples after cutting thin sections of carbonate rocks, during the current investigations (Plate 12, e, f and g). A fluid inclusion study showed the presence of contained oil and gas within diagenetic cements in stratigraphic drillhole Amoco 83-4, and provided an indication of migration timing relative to diagenesis (Lisk et al., 1991).

A possible seismic direct hydrocarbon indication was recognised under the site of Egilabria-1. Two forms of DHI are present. The first is a broad trough at the level of the spill point of the structure (seismic section 89BN-06, Figure 3-29b). The second is a sharp flat peak shown on Figure 3-14c which also occurs at the same level on other seismic sections over the structure. (Compare this indication to the one reported by Enaehescu, 1990). Stone (1977) evaluated the details of various "bright" and "flat" spots on seismic sections where producible hydrocarbons have been proved responsible. From Stone's work it is possible to conclude that the seismic phase change observed at many gas-water contacts closely resembles the phase change on the flat peak DHI under Egilabria-1. Although the flat contact was not penetrated in Egilabria-1, the zone immediately above the flat spot was drilled and found to contain neither producible hydrocarbons nor reservoir. High drill gas methane levels of 400 units (about 8%) were recorded in the zone.

5.4.11 Risk analysis

Risk and uncertainty are inherent aspects of investing in petroleum exploration ventures and these can be broken down into three general areas. The areas are prospect target size, discovery probability, and finding cost (Rose, 1987). To this can be added market availability, a particularly important consideration in the current climate.

Before drilling, the Mount Isa Basin was seen to contain several prospect targets each of the order of 1 TCF gas or 100 MMB oil and many leads. The exploration cost was low, about $10 million for 1000 km of seismic lines in four programs and four exploration wells (1400 m, 1500 m, 2000 m, and 2500 m deep) in two programs. With a beckoning and expanding metal processing market in the area the only significant unknown was the discovery probability which although high risk, based on the above technical analysis, was a definite possibility.

Assessment of the drilling technique to be employed is an important technical and economic consideration in any grass-roots exploration program. An analysis of the selection process is presented in Appendix 2. The exploration drilling method chosen to evaluate the northern Mount Isa Basin was conventional rotary petroleum drilling as this was best suited to undertake the evaluation in the light of the various requirements and risks.

The details of the risk analysis are presented in Appendix 3.

5.4.12 Gases associated with petroleum

Artesian water degases spontaneously due to pressure reduction as it flows to the surface, producing bubbles and effervescence in various amounts. The deeper bores are usually hotter and release more gas than those at shallower depths.

Two major waterbore gas studies have been undertaken in the Carpentaria Basin to assess the hydrocarbon exploration potential on a regional basis (Bourke and Hodgson, 1984; McConachie, 1987a). Several waterbores studied are located within or adjacent to the northern Mount Isa Basin, but one in particular is the Burketown waterbore. The bores produce water mostly from the overlying Carpentaria Basin or undefined pre-Jurassic strata immediately below. As part of the above referenced studies, helium, hydrocarbons, oxygen, nitrogen and carbon dioxide were analysed with the results normalised to a "air free" basis to account for atmospheric contamination. This was done by equating measured oxygen to air, and adjusting the nitrogen and other gas levels appropriately. Most samples contained undetectable oxygen levels attesting to the quality of the sampling technique used. Potentially economic helium levels were observed in many samples.

Analyses

Helium can be analysed by several methods with varying sensitivities. Mass spectrometry is capable of detecting minute concentrations and robust field units are commonly used for leak detection in pipelines (Albers and Rose, 1985; Willard et al., 1974). Gas chromatography utilising an argon carrier gas is routinely employed to analyse helium concentrations above 0.1%. The only potential interfering element is hydrogen, which due to its comparable molecular size, has a similar column retention time. Hydrogen is very rare in natural gas, but may be produced by casing corrosion. The presence of hydrogen is readily determined by gas chromatography using helium as the carrier gas.

The helium levels in the water bore samples were analysed by gas chromatograph using argon as the carrier gas. Care was taken to achieve good separation of the hydrogen and helium peaks before helium analysis and separate checks for hydrogen were run. No hydrogen was detected.

Characteristics and Origin

Helium is a monatomic gas which undergoes few reactions (Crockett and Smith, 1973). Although it diffuses more rapidly and flows through an orifice more rapidly than any other gas except hydrogen, the rate of diffusion through solid containers such as glass or stainless steel is negligible (Altemose, 1961). This colourless, odourless, tasteless gas is the only element that cannot be solidified under atmospheric pressure; although it is not difficult under higher pressures. Lack of chemical reactivity, low temperature as a liquid and low neutron absorption cross-section are the unique properties of helium. Its important physical properties are summarised in Table 5-6.

Property	Value
Atomic number	2
Atomic weight	4.002
Melting point at 25.2 atm pressure	1.1 K
Boiling point at 1 atm pressure	4.22 K
Gas density at 0°C, 1 atm pressure	0.17847 g/L
Liquid density at its boiling point	0.1249 g/L

Table 5-6. Properties of helium

On a cosmic scale, helium comprises 23% of the universe but only 8×10^7 wt% of the earth's crust. Three isotopes are known, ^{3}He, ^{4}He and ^{6}He, but only the first two are stable. ^{3}He is relatively uncommon and is produced by beta decay of tritium in atmospheric and geological sources. ^{4}He, the dominant isotope is primarily a product of radioactivity of uranium and thorium (Voronov et al., 1975; Riley, 1980; Ozima and Podosek, 1983). Helium in natural gas deposits is primarily formed by radioactive decay (Jodry and Henneman, 1968; Zartman et al., 1961), although possible primordial occurrences are known (Phinney et al., 1978). In the atmosphere, helium is present at a background concentration of 5.24 µL/L. It is constantly emanating from the solid earth, however escape from the upper atmosphere prevents accumulation.

Based on isotopic ratios, helium in natural gas fields is primarily of radiogenic origin (derived from uranium and thorium), but it is unclear if the source is from synsedimentary rocks (Pereira and Adams, 1982) or radioactive basement rocks (Hunt, 1979; Burwash and Cumming, 1974; Voronov et al., 1975). Alternatively, both could be sources in various geological situations (Hobson and Tiratsoo, 1981). Nikonov (1973) noted that helium-bearing gases are usually found in uranium-bearing provinces, but no direct relationship between the uranium concentrations and the helium content has been established. Jodry and Henneman (1968) and Tissot and Welte (1978) observed that the average helium content in well gases increases with the age of the reservoir rocks, from the Tertiary to the Palaeozoic. This could be a function of the half lives of the radioactive elements or simply that the older rocks tend to be nearer basement where the radioactive source potential is greatest.

Associations of helium with nitrogen are common in the literature, and Nikonov (1973) recognised a distinct bimodal distribution in reservoir types. Uniquely high helium concentrations are observed in nitrogen-rich gases, but this situation is far rarer than helium associated with hydrocarbon bearing gases. In hydrocarbon gas type helium deposits, high helium concentrations often occur with relatively low nitrogen levels.

Based on a study of oil and gas basins of the former USSR, Gutsalo (1970) noted the stimulating effect of hydrocarbons on the liberation of helium from minerals and the increased solubility of helium in a mixture with methane.

From a study of the US helium-bearing gas fields, Nikonov (1973) concluded that the most likely places to find helium deposits are large platform structures above ancient protrusions of crystalline basement, primarily granites, in zones with oil and gas. This conclusion can be related to the northern Mount Isa Basin to the extent that before the current study, these ancient Proterozoic rocks were considered crystalline basement.

Implications

Natural gas fields provide the only commercial source of helium. The richest fields occur in the mid-continental Permian carbonates of the Oklahoma Panhandle area of the USA, in Texas, Oklahoma and Kansas. The sedimentary sequence in the Panhandle area pinches out over a major granitic fault block. Another significant area is the Tip Top Field in the Green River Basin of Wyoming. This field occurs in an Ordovician to Permian sequence over the crestal part of the La Barge Platform. This field is believed to contain in excess of 1.3 billion m^3 of helium at 0.8% concentration in low heat value natural gas. In the richest gases, the helium concentration ranges up to 8% (Dobbin, 1968) with the highest reported value being 37% at Thatcher, Colorado (Barker, 1985).

The lower economic limit for commercial helium extraction in the USA is about 0.3% when the helium is present in a combustible natural gas field (Clark, 1981; Foster, 1979; Leachman and Tully, 1983). If the helium is present in a non-flammable gas mixture, the concentration required for economic extraction could be as high as 2.0% although factors such as reserves, logistics and energy availability need to be considered. McConachie (1987a) calculated that one cubic metre of non-flammable gas containing 2% helium has approximately the same dollar value as the equivalent volume of typical flammable natural gas.

Helium analysis of waters and soils has been used as an exploration technique for uranium deposits (Pogorski and Quirt, 1980; Zaikowski and Roberts, 1981), to map fracture zones (Ovchinnikov et al., 1972; Eremeev et al., 1972; Roberts and Roen, 1985) and to delineate known helium-rich hydrocarbon deposits (Reimer et al., 1980). The technique commonly employs a mass spectrometer type gas sniffer with a typical gas reservoir anomaly of 10 mL/L helium concentration above the ambient air background of 5.24 mL/L. High average helium values outside potential reservoir areas have been cited as the reason that helium geochemistry has failed to detect some known hydrocarbon reservoirs (Roberts and Roen, 1985).

Helium in Australia

Henry (1982) Indicated that the highest recorded analysis for helium in Australia was 0.5% in a show of gas in the Meda No.2 well in the Canning Basin. The Woodada gas field in Western Australia is reputed to contain above 0.25% which is almost commercial.

Ball (1928) reported the only known helium occurrence in Queensland from Roma where 0.04% was present.

Results

Although the results of the widespread study by McConachie (1987a) demonstrated high helium levels in several areas possibly related to the Mount Isa Basin, by far the highest level recorded was in the Burketown waterbore (Queensland Water Resources Commission registered number 330) where 7.1% was present in one sample and the other three samples each contained more than 5.2%, all by far the highest values ever recorded in Australia. Interestingly, from a hydrocarbon perspective, these gases also contained between 20% and 70% methane. McConachie (1986a) and Cloake (1986) provided a brief review of this commodity and its development potential in north Queensland.

The significance of the high helium values associated with the northern Mount Isa Basin remains obscure, but both the presence of uranium deposits in the area and the geological setting of the basin creates an intriguing possibility for exploration potential. Recent work by Pacific Oil and Gas has resulted in the discovery of high helium levels associated with sub-commercial gas discoveries in the McArthur Basin.

5.5 RESULTS AND PERSPECTIVES OF THE PETROLEUM EXPLORATION

Unfortunately, Beamesbrook-1, Desert Creek-1, Argyle Creek-1, and Egilabria-1 all failed to locate commercial hydrocarbons, although oil shows and high drill gas levels were observed. The lithology logs and gas curves are presented in Enclosure 7 along with several core logs from existing mineral wells, in Enclosure 8, to illustrate the formations penetrated. Finally, high maturity levels with very narrow oil windows, failure to preserve any early generated hydrocarbons, gas leakage over the long time span of the basin, and inability to preserve reservoir due to extensive diagenesis and lithification, are all believed to have contributed to the lack of economic success of the hydrocarbon exploration program in the northern Mount Isa Basin. Many of these factors could not be predicted without good drillhole control. The complete lack of reservoir at each wellsite was a critical problem.

The exploration work to date cannot conclusively prove that no commercial hydrocarbons are present in the area, particularly as follow-up targets remain in untested areas where some reasons for this initial failure are less significant. The difficulty for the future simply is that the upside potential and reward for success becomes less with each dry hole and therefore the incentive to continue exploration on the basis of the above defined play concepts is greatly reduced.

The importance of hot brine transport through the major former aquifers of the basin cannot be overemphasised. The presence of mesophase in Argyle Creek-

1, indicates enclosing rock temperatures reached over 350°C, while oil bleeds in the overlying South Nicholson Group (suggesting temperatures <150°C) occur today only 300 m higher in the well, and oil bleeds are found in the same formation 30 km to the northwest. All this combines to suggest the activity of hydrocarbon-destroying, metal-carrying hot brine movement late in the foreland depositional phase of the basin. Gize (1986) described the development of mesophase in bitumens from several ore deposits throughout the world. While this augurs well for the base metal potential of the northern Mount Isa Basin, the hydrocarbon prospectivity must be considered poor. As no commercial gas was discovered, the helium potential of the area could not be confirmed.

6 METALLIFEROUS GEOLOGY OF THE NORTHERN MOUNT ISA BASIN

6.1 METALLOGENIC MODELS FOR FLUID-DERIVED BASE AND PRECIOUS METALS HOSTED IN SEDIMENTARY ROCKS

Rift sequences, such as under the Red Sea (Hamilton, 1973; Degens and Ross, 1976) and at mid-oceanic ridge spreading centres (Rona, 1986), are known to host strata-bound and epigenetic metalliferous deposits. By contrast, large scale epigenetic base metal mineralisation occurs beneath the Mississippi Valley (Hagni, 1976) and the Appalachians (Hoagland, 1976). Various models therefore exist to account for the production, movement and precipitation of ore-bearing fluids, but in a rift-drift-peripheral foreland basin like Mount Isa, only particular models could have been applicable at particular times in the basin's history.

Spreading centre magmatic fluid sourcing into the rift sequence, hydrodynamic basin fluid flow into the passive margin and foreland sequences or intrusive magmatic sourcing are the three viable mechanisms. Because of the pre-eminent status of the rift basin model to date, rift style mineralisation models have been most commonly proposed (e.g. Sweet, 1983; Derrick, 1991).

6.2 THE REGIONAL PICTURE AND ORE DEPOSIT TYPES

Many similarities exist between the mineralisation styles of the Willyama Block, the McArthur Basin and the Mount Isa Basin. This is hardly surprising in view of the close genetic relationships of each of these areas as described previously (Section 3.4.4, The Carpentarian Superbasin). The discussion which follows concentrates on the northern Mount Isa Basin and the Mount Isa Basin in general, but also uses data and observations from other areas of the Carpentarian Superbasin where appropriate.

Derrick (1991) recognised five classes of mineralisation within the Mount Isa and McArthur Basins. These are presented (slightly modified) in the following Table 6-1.

Category	Mineralisation	Examples
Sediment(shale)-hosted exhalative/diagenetic	Pb-Zn-Ag	Mount Isa, McArthur River (HYC), Lady Loretta, Century, Hilton, Hilton North, ?Dugald River, ?Bulman
Sedimentary-BIF-associated exhalative	Pb-Zn, Cu-Au	Soldiers Cap Group (similar to Broken Hill), Starra (Selwyn)
Vein-stockwork, shear-related	Cu, Pb-Zn	Mount Isa Copper, Silver King
Stratabound sandstone-siltstone-hosted copper	Sub-economic Cu	Surprise Creek
Granite related	U, Pegmatites	?Mary Kathleen

Table 6-1. Ore body category, mineralisation type and examples from the northern Mount Isa Basin (after Derrick, 1991)

The following discussion concentrates on the "sediment(shale)-hosted exhalative/diagenetic" McArthur Type (Williams, 1980) and the sedimentary-BIF-associated exhalative type mineralisation, and to a lesser extent the "vein-stockwork, shear-related" Mount Isa Copper type deposits. The first two are the mineralisation styles with the greatest likelihood to have formed early in the history of the Mount Isa Basin when the sequence was relatively undeformed, like the Bowthorn Block today.

The problems of recognising the differences between syngenetic and epigenetic ore types is common to gold (Pretorius, 1976; Phillips et al., 1987; Phillips et al., 1989; Phillips and Myers, 1989) and base metals (Large, 1991; Hagni, 1976). The base metal deposits of the Mount Isa Basin have at various times been interpreted in different ways.

6.2.1 Regional geological setting of the McArthur, Century, Mount Isa and Broken Hill areas

Each of these areas host stratiform massive base metal sulphide deposits which are mainly fault bounded or isolated structures with a range of lateral dimensions. Mineralisation is commonly located close to these fault zones in morphological traps (called third-order basins, Large, 1983; but more appropriately considered synclines) with dimensions of about a few kilometres.

Mookherjee (1976) described the textural-structural and mineralogical-chemical changes produced by regional metamorphism of sulphide deposits. The mineral deposits and host sequences within the Broken Hill, Mount Isa and McArthur areas can be considered regionally metamorphosed, but temperatures trend from low, essentially unmetamorphosed, at McArthur River (HYC) deposit in the McArthur Basin (very fine grained), to high (and coarse grained) at Broken Hill. Once metamorphic temperatures exceeded the ore emplacement temperatures, thermal overprinting of the ore and associated rocks would mask any effects produced during deposition.

Throughout each of the mineralised Carpentarian Superbasin areas there are thick sequences of rift related basic volcanic and volcaniclastic rocks in the stratigraphic groups underlying the sedimentary sequences that host the base metal deposits. The deposits themselves are mostly contained within thick clastic foreland or carbonate passive margin sedimentary sequences although minor copper and uranium deposits also occur, for example, in the Eastern Creek Volcanics.

6.2.2 Gangue and associated minerals

In the Mount Isa Basin, gangue consists of relatively unaltered, mostly unmineralised adjacent country rock. At Mount Isa, copper is associated with silica-dolomite while the lead-zinc occurs with pyrite, in carbonaceous sedimentary rocks. In the case of the other large base metal deposits of the

Carpentarian Superbasin the associated rocks were or are carbonaceous (Saxby, 1976) suggesting a possible genetic link that was, before this thesis, rarely considered.

At Broken Hill, the Pb-Zn orebody gangue includes magnetite-garnet-quartz-apatite, quartz-garnet and quartz-fluorite (Stevens et al., 1990). Plimer (1992) described the Broken Hill orebody as comprising of horizons of sulphide rocks of unusual composition. Intercalated with, and stratigraphically equivalent to the sulphide rocks, are quartz-rich horizons enriched in zinc (gahnite, sphalerite), manganese (spessartine), iron (oxides, silicates), boron (tourmaline) and lead (plumbian microcline) and calc-silicate rocks enriched in barium and tungsten. Meta-evaporites are considered to have made up an integral part of the sequence.

Scapolite, which indicates altered evaporite sequences, is common at Dugald River in the southern Mount Isa Basin. Other alteration effects are related to reactions with evaporites (Derrick, 1991) and these may be more common than realised. Connor et al. (1982) described the Dugald River deposit, its metasedimentary host rocks and major element geochemistry in detail.

Pyrite is the most common gangue sulphide in the Mount Isa Basin, but detailed studies have shown that much of this formed early, before the introduction of the economic metal sulphides (Neudert, 1983). Derrick (1991) noted that strong synsedimentary pyrite development is a feature of McArthur Type mineralisation. Despite this, pyrite associated with mineralisation is sufficient to give rise to significant sulphur isotope problems (Dr M.D. Muir, pers. comm., 1993).

North of the Mount Isa Basin geochemical halos exist in the host rocks around the McArthur River deposit. Manganese is enriched in carbonates (1000-2000 mg/L against a background of 400 mg/L) while zinc and lead are enriched in host sedimentary rocks for several kilometres.

6.2.3 Age of mineralisation

Figure 3-6 (Section 3.5, Chronostratigraphy) shows the ages of most of the dated intrusions within the basin. Additional dating of Mount Isa and McArthur River (HYC) deposits indicated depositional ages of 1670 Ma and 1690 Ma respectively (Page, 1981), with overlapping error bars.

Latest dating by Dr. R. W. Page pers. comm. (1993) of the AGSO suggested the date for the Sybella Granite at Mount Isa is 1655 to 1671 Ma for various phases and the age of the tuffs in the Mount Isa ore deposit is 1653±7 Ma. The first pass age determination for Century is about 1620 Ma (Mr G. Broadbent, pers comm., 1992).

The spread of dates generally conforms to the interpreted stratigraphic superpositions of the various rock sequences in the northern Mount Isa Basin.

The extent to which mineralising fluids may overprint rock dates is uncertain, but since the ages are based on tuffaceous layers within the mineralised sequences, the effects should not be great.

6.3 MAJOR BASE METAL DEPOSITS (Pb-Zn with associated Ag)

Figure 6-1 shows the location of many large potential and producing mines of the Mount Isa region. Hundreds of small scale deposits, some of which are prospects, are also known.

The McArthur River, Century, Lady Loretta, Mount Isa, Dugald River, Cannington and Broken Hill deposits are all located close to major faults. The reactivation of these fault zones has lead to the formation of distinctive lineaments. Some of the faults, although they run at angles which are not suggestive of syndepositional structures, have attributes of growth faults and may have been inverted or active during sulphide mineralisation. During movement within such fault zones, both dilation and compression can occur and so some areas will have been favoured for the ascent and concentration of hydrothermal solutions. Despite the proximity of all these major deposits to faults, a definite genetic link is far from certain.

Klein (1991b) proposed a general inorganic geochemical basin classification which is shown in Table 6-2. The known characteristics of the Carpentarian Superbasin based on the depth-related geothermal gradient and rift source rock potential of various areas are highlighted together with the hydrodynamic system of the proposed basin model determined for the northern Mount Isa Basin.

Metal Solubility Factor	Migration Drainage Factor	Environmental Potential for Mineral Precipitation
Low solubility	Vertically drained (Within orogen)	Low potential for hydrodynamic brine movement
Moderate solubility	Laterally drained (Within foreland)	Moderate potential for hydrodynamic brine movement
High solubility		High potential for hydrodynamic brine movement

Note: Highlighted areas indicate Carpentarian Superbasin parameters

Table 6-2. Inorganic geochemical basin classification for sediment hosted ores (from Klein, 1991b)

6.3.1 The major base metal deposits of the Carpentarian Superbasin (Broken Hill, Mount Isa, Hilton, Hilton North, Dugald River, Lady Loretta, Century, McArthur River-HYC)

All of these deposits were comprehensively described by various authors in Hughes (1990), and earlier work on most areas was reported in Knight (1975) and Edwards (1953). Mount Isa and Hilton, the two best known deposits in the Mount Isa Basin were comprehensively described by Carter (1953), Mathias et al. (1971) and Bennett (1970 and 1965). The geology of McArthur River was described, along with its regional setting by Lambert (1976), Muir (1983), Pietsch et al. (1991a and b). Both and Rutland (1976), Barnes (1988), Stevens et al. (1990) and Beeson (1990) have described regional studies of Broken Hill. Details of the various deposits are tabulated in Williams (1980) and Barnes (1988).

Many very large lead-zinc-silver deposits occur throughout the Carpentarian Superbasin. Their distribution appears to be coincident with a major geophysical lineament, The "Lawrence Lineament" (CRA Exploration in-house term) connects Broken Hill, Mount Isa, Century and McArthur River. The trend features decreasing lead-zinc grain size to the north in the direction of decreasing metamorphism. It represents the linking of several major faults (Corona, Mount Isa, Termite Range, Calvert and Emu Faults). This may be a fundamental thick skin tectonic feature of the Carpentarian Superbasin which has either controlled ore deposition or merely exposed the basin sequence along its length.

6.3.2 Mineralisation associated with the northern depositional margin of the Mount Isa Basin and the adjacent Murphy Inlier

Ahmad and Wygralak (1989 and 1990) described the various deposits of this area and the adjacent sedimentary section of the Mount Isa and McArthur Basins. Uranium, copper, tin-tungsten, lead-zinc, microdiamonds and gold have been reported. Most occur within the basin sedimentary rocks next to the Inlier, but some occur in the basement rocks of the Murphy Inlier itself which may have acted as fluid traps when previously covered by thin Mount Isa and McArthur Basin rocks.

Lead Hill Prospect

Lead Hill, which is misnamed, is located on the bank of Wire Creek about 4 km north of drillhole Esso GCD-1. The conspicuous lateritic conglomerate which caps the hill does not host lead mineralisation (Plate 14, a). The Lead Hill Prospect as described in many mineral exploration reports (e.g. Billington, 1991a; Rowley, 1983) actually refers to pockets of galena mineralisation within a 15 metre high, 2 to 4 metre wide vertical joint or breccia zone (Plate 14, b) in the Mount Les Siltstone on the east bank of Wire Creek, a few hundred metres south of Lead Hill summit on the western side.

Sampling by Taylor (1970) indicated an average grade of 10% Pb for the main mineralised breccia zone. Despite this high grade, the deposit is too small to be worked economically.

Taylor (1970) also suggested that the breccia was formed by solution collapse, but the field evidence does not support this interpretation. The fracture infill style of the mineralisation, and the clastic host rock both suggest a tectonic origin. Rowley (1983) recognised a series of gentle folds in the Mount Les Siltstone with the axis of one syncline trending west-northwesterly, almost directly through the Lead Hill Prospect. He considered that the breccia represented fault movement along this axis. There are several series of lineaments visible on aerial photographs within 1 km^2 around the prospect. One set, following the present course of the creek, trends north-northwesterly. These lineaments can be traced across the Fish River Fault Zone. A second set that appears correspond to Rowley's (1983) fault, trends approximately east-west. Collectively, these lineaments represent a considerable density of faults near the prospect.

Similarly sized, steeply discordant, but unmineralised breccia occurs within the Walford Dolomite about a kilometre north of Lead Hill, where it forms the wall and roof of a cave overlooking Gorge Waterhole. This breccia is almost certainly associated with splinter faults from the nearby Fish River Fault Zone. Although many of the details of Walford Creek Prospect are currently still confidential to Western Mining Corporation, the mineralisation there quite possibly relates to a similar splinter zone in the Mount Les Siltstone. Extensive follow-up drilling at the Walford Creek Prospect by Western Mining Corporation was reported to have failed to detect substantial mineralisation (Webb and Rohrlach, 1992).

Other Mineralised Prospects

A range of small lead-zinc deposits have been recognised along the strike length of the Walford Dolomite/Mount Les Siltstone outcrop (Rowley, 1983). Names include Gorge Creek, Mount Les, Galena Pits and First Up. None is as rich as Lead Hill, and only Galena Pits was inspected in the field.

Polycarpaea glabra and spirostytis (locally known as zinc weed), a geobotanical indicator of acid mine drainage type soil conditions (Mr G. Broadbent, pers. comm., 1991), are common in the Bowthorn Block of the northern Mount Isa Basin (Plate 14, c). These plants are considered possible indicators of mineralisation throughout the northern Mount Isa Basin.

Further local scale exploration work in the area is being undertaken by many companies.

Deposits within the Murphy Inlier

A range of small scale mineral deposits within the Murphy Inlier have been described by Ahmad and Wygralak (1990). Deposits and shows include copper, tin-tungsten, uranium and gold, mostly as small-scale epigenetic deposits.

6.3.3 Mineralisation in the Riversleigh Fold Zone

The major deposit in the Riversleigh Fold Zone of the northern Mount Isa Basin is the newly discovered Century ore body located close to the Termite Range Fault (Main, 1991; Thomas et al., 1992). Several small scale breccia and fault controlled deposits in the Century area include Silver King, Lilydale (Plate 14, d) and Watson's Lode. To the north, several other small deposits occur.

The Lady Loretta lead-zinc deposit is located further south, but still within this structural zone. The orebody there is contained in a tight syncline.

Hutton and Sweet (1982) reported that copper shows exist at various stratigraphic levels in the Riversleigh Fold Zone. These deposits include Lady Annie, Lady Agnes, Mammoth, Mount Gordon, Mount Oxide and Jack McNamara. All are small in size and epigenetic in character, but they do indicate the potential of this part of the basin.

Active exploration is continuing in this region.

6.4 Other Mount Isa Basin related mineralisation

A wide range of metals has been mined in small quantities throughout the southern part of the Mount Isa Basin where faulting has resulted in the surface exposure of much of the stratigraphy, but less is known from the northern part of the basin. The basin and ore deposition models presented in this thesis imply that the most significant difference between the two regions is the relative lack of fault exposure at the surface, because base metal mineralisation appears to have predated much of the faulting. The lack of regional metamorphism in the northern Mount Isa Basin suggests lower overall temperatures prevailed and this resulted in preservation of the original fine grained mineralisation. Because of the large scale of the deposits at Century and HYC in the McArthur Basin, equally vigorous metal stripping from the various source rocks (and similar hydrodynamic and basin conditions) can be interpreted to have occurred within the northern and southern Mount Isa Basins, southern McArthur Basin and Willyama Block (Basin).

6.4.1 Silver

Silver in the Mount Isa Basin is commonly associated with the base metal deposits. Along with Pb and Zn, Cannington is reported to contain associated silver associated with lead and zinc, greater than previously discovered at either Mount Isa or Broken Hill. Blake (1987) reported that a few silver deposits had been mined including the "Silver Phantom" in the Mary Kathleen Block of the Cloncurry Orogen. This is a roof pendant of Mitakoodi Quartzite in the Wimberu Granite. The deposit consists mainly of cerargyrite, native silver and naumannite in a gangue of barite, jasper, chalcedonic and opaline silica, and dark clayey material.

Two models for silver deposition within the Mount Isa Basin can be postulated. The first is the same as for lead-zinc, primarily because of the close association of the three minerals. The second interpretation applies to the high-grade deposits such as "Silver Phantom" where intrusions may have enriched earlier formed deposits with silver.

6.4.2 Copper

The major copper deposit at Mount Isa was generally considered not to have formed at the time of lead-zinc mineralisation, but to post-date it by some 50 Ma (Swager, 1985). More recently, Perkins (1990) described an epigenetic model for copper mineralisation related directly to the lead-zinc deposition. The Eastern Creek Volcanics have been recognised as a potential source of copper (Wilson et al., 1985) and these rocks also contain anomalous levels of lead and zinc. Near the Mount Isa Mine, the close association of greenstones derived from the alteration of the Eastern Creek Volcanics supports their interpretation as source rocks.

Copper mineralisation appears to have formed at the same time as the distinctly epigenetic silica dolostone host. This is a brecciated sediment-hosted deposit similar to that at Mammoth, Mount Oxide and Lady Annie. Blake (1987) reported that the vast majority of the many copper mines in the Mount Isa Basin are shear and fault controlled vein deposits characterised by small tonnages, but relatively high grades. The main hosts for these epigenetic deposits are carbonaceous and pyritic slates, calc-silicate rocks, metabasalt and felsic igneous rocks indicating a variety of trap styles. Gold, silver and bismuth are commonly associated with these copper deposits.

Maynard (1991d) concluded that sedimentary basin related copper is a product of diagenesis in rifted basins, but it is difficult to relate this model to Mount Isa. Perhaps mineralisation can occur in a range of settings syndepositional, syndiagenetic, post-compactional and syntectonic epigenetic due to basin cannibalisation associated with foreland orogenesis and regional metamorphism. Unrug (1988) proposed a sedimentary basin model for metallogenesis in the Neoproterozoic copper belt of Zambia. He envisaged hydrothermal fluids emplacing the Cu-Co, Zn-Pb, U, Au and noble metals into normal basin aquifer systems.

Based on the above discussion, the model for copper mineralisation is similar to that for the lead-zinc-silver, but in the case of Mount Isa, the copper was probably deposited into the forming Cloncurry Orogen, as a higher temperature epigenetic deposit than the lead-zinc.

6.4.3 Gold

Davidson et al. (1989) have described Au-Cu mineralisation at Starra (Pegmont) and Trough Tank in the Mary Kathleen Block of the southern Mount Isa Basin. They supported a syngenetic exhalative origin although Laing et al. (1988)

considered that the iron formation and the gold-copper mineralisation were not syn-sedimentary. Laing et al. considered the iron possibly derived from originally syn-sedimentary ironstones as exemplified in other areas of the Selwyn region.

Little detailed information has been reported on other major gold deposits such as Tick Hill. It occurs as a stratiform deposit with high-grade geochemical surface expression. The deposit contains proven ore reserves of 470 000 tonnes at 27 g/t gold (Crookes, 1993).

The basic model for gold mineralisation in this thesis is epigenetic, similar to the lead-zinc-silver and copper, but with the basin fluids sourcing the metal from a deeper, hotter environment more typical of the southern Mount Isa Basin.

6.4.4 Uranium

Maynard (1991c) described uranium deposits of the world in terms of syngenetic to diagenetic deposits in foreland basins. Interestingly he excluded Olympic Dam from this discussion because it is thought to have formed by hydrothermal processes. When this Palaeo- to Mesoproterozoic deposit is placed into its setting in the Carpentarian Superbasin, a possible foreland relationship may emerge.

The major uranium deposit in the Mount Isa Basin is at Mary Kathleen. This is hosted by garnetiferous calc-silicate rocks of the Corella Formation (Blake, 1987). Both syngenetic basaltic (Scott and Scott, 1985) and epigenetic syntectonic, origins have been proposed. These origins have been related to either uranium-rich dykes (Derrick, 1977) or sedimentary pile metamorphism (Hawkins, 1975).

The Pandanus uranium deposit is located in the Murphy Inlier where the uranium mineralisation occurs in shear zones cutting altered Cliffdale Volcanics (Sweet et al., 1981). As this deposit occurs in basement to the northern Mount Isa Basin it is difficult to establish a genetic link to the basin, however thin aquifers of Constance Sandstone may have extended over the area in the past.

6.4.5 Iron formations

The geology of the Constance Range low grade iron ore deposits (see Train Range Ironstone, under Section 3.7.4, The upper section of the northern Mount Isa Basin) was described by Carter and Zimmerman (1960), Rowell (1963) and Harms (1965). Similar style deposits called the Sherwin Ironstone Member, located near Roper River in the McArthur Basin were described by Canavan (1965).

Setting and mineralogy

Carter and Zimmerman (1960) described the Constance Range ironstone deposits as sedimentary, iron-rich, generally oolitic beds. Iron minerals described are haematite, siderite, chamosite and pyrite. The pyrite is mainly epigenetic and occurs in thin stringers. Magnetite has not been recorded and was not indicated by aeromagnetic surveys. Haematite mainly appears in oolites, commonly with sand grain nuclei, but also forms part or all the matrix in places. It occurs in two forms, as red ochreous haematite and as blue-black crystalline haematite. Siderite is the main cementing material, but also forms oolites.

Based on extensive drilling and analysis Harms (1965) described the oxidised iron at the surface as giving way to primary ironstones below the present water table. The primary ironstones consist of oolites of ochreous or finely crystalline haematite, siderite and/or chamosite and silica grains set in a matrix of siderite, haematite, minor microcrystalline quartz, and carbonaceous matter. The mineral called chamosite was not specifically identified; it resembles chamosite, greenalite or glauconite, and may include all these minerals. The oolites range from 0.2 mm to 3 mm in diameter and the successive shells are composed of different iron minerals. In the groundmass, siderite commonly forms crystals up to several centimetres across, enclosing oolites and quartz grains. Lower grade ironstones occur where the proportion of clastic silica and/or silt to clay increases, and in general these lower grade ironstones contain a higher proportion of siderite and/or chamosite. The oolite-to-matrix ratio is variable, and the individual laminae within the ironstone lenses grade from nearly pure haematite to nearly pure siderite. Chamosite is rare within the economically important parts of the beds, but is more common in the siliceous and shaly sections, where it commonly constitutes the bulk of the iron minerals. It commonly occurs in intraformational conglomerate layers, as flattened concretionary pellets of irregular shape with a maximum dimension of as much 1 cm.

Depositional environment

Harms (1965), after Carter and Zimmerman (1960), interpreted the depositional environment of the ironstone to be a shallow barred basin in which, at sudden but relatively infrequent intervals, and for varying periods, iron minerals predominated in the sediments being deposited. Shallow water conditions are indicated by mudcracks, ripple marks, cross-bedding and intraformational mudstone conglomerates in the sediments associated with the ironstone beds. The oolites presumably formed around quartzose or other nuclei by the rolling action of currents, the nuclei being coated progressively by semi-gelatinous iron precipitates probably related to bacterial precipitation.

Analogues

Based on the work of Maynard (1983), it appears that iron generally is concentrated in a variety of deposit types. The largest from which most modern production is derived are of two types: banded iron formations (BIF's) and oolitic ironstones. Gross (1980) recognised two types of BIF; the Algoma type which is relatively small with an obvious volcanic association (abundant in the Archaean), and the Lake Superior type, which is much larger and has a shallow shelf, orthoquartzite-carbonate association (confined largely to the Proterozoic). Oolitic ironstones have a more clastic association than the BIF iron-formations, and have more alumina in them. Instead of layers, their most prominent sedimentary structure is oolites consisting of haematite, goethite or chamosite. Chert is rare. Oolitic ironstones are found with a variety of ages from Proterozoic to Pliocene, but are more common in the Phanerozoic.

Maynard (1983) described oolitic ironstones as consisting of goethite, chamosite, or both. Siderite, and less commonly apatite, may occur as rare thin laminae, but siderite is more commonly seen as a matrix between the ooliths or as a replacement of pre-existing chamosite or goethite ooliths; no primary siderite ooliths have been recorded. Chamosite is virtually the only iron silicate encountered in ironstone deposits. Similar mineral species such as glauconite and greenalite are very rare. Greenalite is probably absent because the sediments in which the ironstones formed were too rich in aluminium. Glauconite, which is never oolitic (Maynard, 1983), is commonly present in iron-rich sedimentary rocks, but almost never found in oolitic ironstones. Glauconite is also aluminium-rich relative to chamosite.

The ooliths in ironstones are commonly flattened or irregular in shape (Maynard, 1983). Knox (1970) concluded this flattening was a result of differing growth rates rather than deformation. Knox concluded that ooliths did not form by accretion in agitated water, but in relatively quiet water from which they subsequently washed up into oolite shoals. Deformed ooliths have been recognised in the Train Range Ironstones (Harmes, 1965).

Maynard (1983) concluded that oolitic ironstones occur almost exclusively in clastic sequences. Further, their position is usually close to the shoreline, even brackish in some cases; they also correspond in time to thicker sections in other parts of their basins of deposition. Most authors assign the Clinton oolitic ironstones to a foreland basin setting (Van Houten and Arthur, 1989). Hamilton (1973) described a small Oligocene oolitic ironstone deposit associated with the Red Sea rift at Wadi Fatima.

Carter and Zimmerman (1960) compared the Constance ironstones with the Ordovician ironstones at Wabana, Newfoundland, the Silurian Clinton Formation in the eastern USA and the Jurassic ores of Britain and France. Harmes (1965) reported that the Wabana ironstones of Newfoundland contain up to 1 per cent phosphate due to the presence of marine animal fossils. The Constance Range and Roper Bar ironstones have a phosphate content less than

0.05 %, but contain carbonaceous matter, possibly reflecting an abundance of algal remains in the Proterozoic rather than the animal remains which characterise the Phanerozoic deposits.

Clemmey (1985) considered oolitic iron ore formation generally to be a characteristic feature exclusive to Phanerozoic basins. This is not supported by the large Mount Isa and McArthur Basin deposits. Bonner and Chauvel (1979) produced an international stratigraphic table of Precambrian iron ore deposits illustrating the global deposit setting of the Constance Range ironstone. Although other Proterozoic oolitic ironstones have been reported in Africa (Button, 1976), the Silurian age Clinton ores of the eastern USA appear to be most closely analogous to the Train Range Ironstone of the northern Mount Isa Basin.

The detailed description of Clinton ore of the Appalachian Foreland Basin which follows is based on descriptions by Maynard (1983) and Maynard (1991a). Maynard (1983) stated that the only regional sedimentological description of the Clinton ores is that of Hunter (1970). The ironstones predominantly are found in what appear to have been lower intertidal to shallow subtidal areas. Hunter divided the Clinton Group into eight facies based on mineralogy. Ironstones were best developed in shallow subtidal environments. Offshore bars, although present (Folk, 1962), do not appear to have been important in localising the ironstones. Each episode of ironstone deposition seems related to a general shallowing of the basin: ironstones in the distal part of the basin correlate with a tongue of sandstone prograding from the southeast and with an expansion of the carbonate facies. During late Clinton time, the style of deposition changed to more open marine. The *Lingula*-bearing chlorite- and haematite-cemented sandstones were succeeded by carbonate-cemented sandstones with a normal shelf fauna, and the green shales were succeeded by more organic-rich gray to dark gray shales. The best development of the Clinton ores is in the southern Appalachians near Birmingham, Alabama. Chowns and McKinney (1980) presented a description of the facies succession. Three coarsening-upward, progradational cycles can be recognised, each culminating in ironstone deposition. The cycle begins with prodelta turbidites and shales, which pass upward into hummocky cross-bedded sandstones with interbedded shales. This facies is interpreted as having been deposited below normal wave base, but in sufficiently shallow water to be affected by storms. Above these is a shallow subtidal facies consisting of medium to coarse sandstone, coated with haematite and cemented with quartz. It seems to correspond to Hunter's (1970) silica-cemented sandstone facies. Cross-bedding in this facies is bipolar, as at Wabana, indicating tidal currents, and the trace fossil assemblage is mixed *Cruziana-Scolithus*. To the west, this facies passes into rich ironstone beds comprising abraded fossil debris in a haematite matrix. Oolitic ore beds are not common, but a few chamosite oolites and haematite-replaced chamosite oolites are known. Sheldon (1970) considered that, just as in the Ranger (1979; quoted from Maynard, 1983) model for Wabana, the ore-grade beds were formed in lagoons (chamosite) or barrier bars (haematite). He further advocated an origin of the haematite by replacement of earlier-formed chamosite.

A depositional model for the Train Range Ironstone

The Train Range Ironstone of the Constance Range in the northern Mount Isa Basin is interpreted to have been deposited in shallow marine to lagoonal fluvio-deltaic setting. Based on field mapping and drill log reinterpretations undertaken for this thesis, the thicker, carbonaceous siltstones and mudstones which contain the ironstones are interpreted to represent distal prodelta and interdistributory bay fill deposits, while the overlying sandstones (Middle Creek Sandstone etc.) are considered prograding distributary mouth bar and channel deposits. This is evidenced by the coarsening upward character of the sequence, albeit poorly developed (Figure 6-2), and the erratic distribution of the channel sandstone deposits. Unlike modern deltas, which by comparison are stabilised by terrestrial and marine vegetation, much more braided Proterozoic channel sandstone character is apparent. During the deposition of the ironstone, it is probable that cooler temperatures prevailed because no laterally equivalent carbonates appear to have developed, although this may relate to water chemistry and other environmental factors.

No ironstones have been reported to occur in the Lawn Hill Formation which is situated below the unconformity at the base of the Constance Sandstone. Despite the lack of ironstones, the mild disconformable nature of the basal

South Nicholson Group unconformity in the Bowthorn Block, combined with the fluvio-deltaic character of the Constance Sandstone, clearly suggest that the Pmh$_6$ unit at the top of the Lawn Hill Formation could be a syn-tectonic, distal, possible basin fill facies equivalent. In this model, the South Nicholson Group molasse would have been deposited proximal to the northerly migrating orogen. The Train Range Ironstone was either not deposited in, or has possibly been eroded from, the Bowthorn Block of the northern Mount Isa Basin. The Argyle Creek-1 drillhole intersected glauconite-rich (possibly chamositic) sandstone in the South Nicholson Group in the Bowthorn Block.

Ironstones in the Carpentarian Superbasin

The possible origins of the northern Mount Isa Basin ironstone were discussed by Harms (1965). Sturesson (1992) concluded that volcanic ash (which has poor preservation potential in ooid forming environments) was the source rock for Ordovician chamositic oolites in Sweden. The source of the Train Range iron ore is speculative, but siderite gangue is present in zinc mineralisation in the Lawn Hill Formation. Small galena veins occur in the lower Mullera Formation, which conformably underlies the Train Range Ironstone Member. Iron mineralisation may therefore have been produced by a similar basin-related process to the lead-zinc deposits, but precipitated under different conditions.

In the southern Mount Isa Basin bedded ironstones are hosts for copper-gold mineralisation at Pegmont and lead-zinc at Dugald River. Blake (1987) noted that subeconomic iron-rich metasedimentary rock-hosted stratiform lead-zinc prospects are present at Pegmont, Dingo and Fairmile. These are not far from the newly discovered BHP deposit of Cannington. The mineralisation occurs in metamorphosed banded iron formations within the Kuridala Formation and Soldiers Cap Group and is considered to be syngenetic exhalative in origin. As first pointed out by Derrick (1976), it shows striking similarities in ore mineralogy, gangue minerals, country rocks, metamorphism and age to the lead-zinc mineralisation at Broken Hill (Haydon and McConachy, 1987; Beeson, 1990).

Whether the Broken Hill and Pegmont ironstones are stratigraphically equivalent to the South Nicholson Group ironstones or to their now eroded equivalents, is difficult to assess at this stage. The gross lithostratigraphic equivalence of Broken Hill (Haydon et al., in press) to the northern Mount Isa Basin looks very convincing. Examining the various ironstones at Mount Isa and Broken Hill for relict oolitic textures could be useful. James (1955), studying the Lake Superior "iron ranges", recorded a progressive increase in grain size with increasing intensity of metamorphism, along with preservation of haematite oolites even up to the sillimanite grade of metamorphism. Deformed iron oolites, development of specularite and/or magnetite knots retaining ghost relicts of oolites, magnetite porphyroblasts, and finally magnetite-quartz ore with distinct form-orientation occur in many Precambrian iron formations that have undergone regional metamorphism.

6.4.6 Manganese

Blake (1987) noted several small manganese deposits, some of which have been mined, that occur in the Overhang Jaspilite of the Mary Kathleen Group.

No deposits have been recognised in the northern Mount Isa Basin. It is possible that at Groote Eylandt to the north-west, Cretaceous (?Tertiary) reworking of Mount Isa or McArthur Basin deposits provided the manganese source for the Carpentaria Basin deposits.

Manganese deposits are more common in the Willyama Block. Johnson and Klingner (1975) described the dominant gangue minerals in the Broken Hill ore body as quartz, calcite and the calcite-manganese-iron silicates, rhodonite, bustamite and manganhedenbergite.

Okita and Shanks III (1992) considered sedimentary hosted manganese oxide deposition in terms of a "bath tub ring" around the margins of mildly anoxic basins. Primary manganese deposits may therefore be present in various sequences of the northern Mount Isa and McArthur Basins. In the McArthur Basin, high levels of manganese are associated with the HYC deposit and the Nathan Group. Element analyses of samples from the 1992 drilling indicated several levels with 1% to 2% manganese in the northern Mount Isa Basin.

6.4.7 Cobalt

The only significant occurrence of cobalt is at Mount Cobalt Mine, in the Mary Kathleen Block of the Cloncurry Orogen. This deposit occurs in a shear zone between a metadolerite sill and steeply dipping meta-sedimentary rock of the Kuridala Formation (Nisbet et al., 1983).

6.4.8 Other deposits

Scheelite, barite, molybdenite and tantalite have all been mined from small deposits in the Mount Isa region (Jones, 1953).

6.5 INTRUSION RELATED MINERALISATION AND THE POSSIBILITY OF MAGMATIC SOURCES

Several intrusions are present either as basement to, or intrusions in the Mount Isa Basin. The major igneous bodies are shown in Figures 3-6, 3-19 and 3-32. Enclosure 9 shows the distribution of volcanic and granitic rocks. The possibility of a syn-foreland magmatic source for the mineralising fluids in the Mount Isa Basin (or the Carpentarian Superbasin) cannot be discounted, but it appears to be unlikely because of the widespread distribution of deposits without associated intrusions. Intrusion-related mineralisation would tend to be patchy and vary regionally due to the incorporation of different basement and basin materials into the various magmas. The temperatures and source rocks necessary to generate the mineralising fluids in the basin could all have been produced naturally in the basin without any necessity for magmatic intervention (c.f. Solomon and Heinrich, 1992).

Some mineralisation may be remobilised by intrusions into the basin, but most older igneous bodies have probably acted as source rocks, while younger ones may have provided fluids to redistribute the existing rift generated mineralisation in the Mount Isa Basin (perhaps producing local skarn deposits in some areas such as Mary Kathleen and Starra).

Only beryl and mica deposits in pegmatites appear to be certainly related to the intrusions in the Mount Isa Basin.

6.6 Characteristics of sediment-hosted McArthur Type and Mississippi Valley Type (MVT) deposits and models

Sawkins (1984) viewed sediment-hosted lead-zinc and MVT deposits as end member variants of general episodic sediment-dewatering process, with the former related to rift basins, and the latter to epicratonic basins. In view of the basin analysis results of the seismic work in the northern Mount Isa Basin it appears that both types are related to major foreland systems. Furthermore, because sediment-hosted and MVT lead zinc deposits are commonly large in size, and both appear to form in foreland basin settings, it is probable that foreland basins hydrodynamics provide an almost unique geometry to allow large-scale transport of metal-rich hydrothermal brines to relatively confined precipitation sites.

Maynard (1991b) considered shale-hosted deposits of Pb, Zn and Ba to be derived from syngenetic deposition from exhaled brines in deep marine basins. He also considered that there are two end member types of Pb-Zn accumulations i.e. clastic sediment-hosted syngenetic deposits and epigenetic mostly carbonated-hosted, (but clearly porosity controlled) MVT deposits. This can be contrasted with the approaches of Morganti (1988) and Anderson and McQueen (1988) who ascribed a distinct genetic model for each type.

Because the Mount Isa Basin is particularly analogous to the Appalachian Basin and each contains vast base metal accumulations, it is useful to compare the major ore deposit characteristics in each basin.

Large (1983) described sediment-hosted massive sulphide lead-zinc MVT and McArthur type deposits as exhibiting the following general characteristics:

1. In morphology the deposits consist of one or more sheets or lens-like tabular bodies up to 10 m thick. Lateral dimensions are at least an order of magnitude greater than the ore body thickness. Disseminated and discordant mineralisation is commonly found underlying or adjacent to the ore body. Although the deposits are small in volume relative to the basins in which they are contained, they are usually high in concentration (McArthur type more so than MVT's).

2. Deposit geochemistries are simple: dominantly pyrite, pyrrhotite, sphalerite, galena, minor chalcopyrite, arsenopyrite and marcasite. Iron sulphides are usually the dominant sulphides present. These metal deposits are usually very fine grained except where metamorphism has caused recrystallisation. Under Australian weathering conditions lead tends to be enriched, and zinc becomes dispersed.

3. The deposits are zoned, and this generally occurs both laterally and vertically (presumably away from the central point in the path of metal bearing hydrothermal solutions where the least soluble sulphides were precipitated). The zonation sequence forms a series of envelopes around a fault zone. Near the fault, in the discordant deposits, mineralisation consists of barite and sometimes tetrahedrite (and minor pyrite, marcasite and chalcopyrite). With increasing distance from the fault, chalcopyrite and pyrite dominate, with sphalerite and galena replacing chalcopyrite further out. A paragenesis of sphalerite, galena and pyrite is finally replaced by sphalerite and pyrite.

4. Stratiform sulphide host lithologies consist of two types:

Autochthonous -- fine grained clastic rocks (shales and siltstones) and/or limestone and dolostone. These lithologies usually show no sign of high energy sedimentary environments. The shales commonly contain relatively high concentrations of organic carbon (more than 5% in the McArthur Basin and probably higher at Century in the northern Mount Isa Basin) as well as pyrite and pyritised fossils that are indicative of the chemically reducing environment in which the stratiform sulphides remain stable.

Allochthonous -- conglomerates, intraformational breccias and coarse clastic sediments commonly interbedded within the fine grained lithologies. The coarse clastic rocks presumably, were rapidly deposited.

Large (op. cit.) also suggested that contemporaneous igneous activity may be significant in terms of both providing mineralising fluids and high geothermal gradients. Penecontemporaneous igneous activity was therefore seen as important in the regional evaluation of these sedimentary basins for mineralisation potential. This concept involves the development of an anomalously high geothermal gradient which is considered a requirement for convective circulation to be developed within the sedimentary pile. This does not really apply in the case of foreland basin settings where the thick, stacked basin fill sequences can produce very high temperatures (>300°C) at the bottom of the sedimentary pile. With thrust-sheet stacking regional metamorphism can further raise temperatures to more than 600°C. Vertical migration is greatly facilitated by faults, but these can act as both migration pathways to sites of ore deposition and pressure release zones for metal remobilisation.

Williams (1980) reviewed the general economic geology, isotope chemistry, and ore formation for the deposits of the McArthur and Mount Isa Basins. Mount Isa, Hilton, Dugald River, Lady Loretta, McArthur River (HYC) and

Bulman lead-zinc deposits (Century and Cannington were not yet discovered) and numerous smaller occurrences all occur in these basins. Williams considered that the many similarities of the various "McArthur" type deposits is strong evidence that their setting is a very significant aspect of their formation. He noted that depositional environments and age of formation were the most obvious similarities. The main features of this deposit type are:

1. The occurrence of one or more stratiform horizons rich in galena and sphalerite, which are hosted by pyritic and dolomitic shales and siltstones.

2. The very fine grain size of the sulphide minerals and their occurrence in laminae parallel to bedding. The pyrite occurs as framboids, and galena and sphalerite occur either interstitially to the pyrite or in non-pyritic laminae.

3. Apparently identical non-sulphide assemblages in mineralised and unmineralised rocks.

While very few MVT deposits have been identified in the Carpentarian Superbasin, their characteristics are similar to McArthur Type deposits. Several small MVT style deposits (Coxco, Cooley and Ridge) occur near the McArthur River deposit. Dr M.D. Muir (pers. comm., 1993) considered Bulman to be a MVT deposit, and described it as coarse grained and silver-rich. It is not associated with ironstone and it occurs in the Nathan Group. It is therefore considered younger than the HYC deposit.

Ohle (1980) reviewed the origin of MVT deposits considering their source rock, timing, temperature and migration characteristics to be similar to petroleum based systems. Kyle (1983) cited the following unifying general characteristics of MVT deposits:

1. Most ore bodies occur as stratabound concentrations in shelf carbonate sequences, usually dolostones, within structural highs on the flanks of major basins.

2. The districts commonly occur at facies boundaries of depositional or diagenetic origin, and the mineralised stratigraphic sequence is typically associated with an unconformity (commonly a subaerial exposure surface).

3. Mineralogy of the deposits is relatively simple, generally consisting of well-formed crystals of sphalerite, galena, marcasite, pyrite, barite, fluorite, dolomite, calcite, and quartz that are the result of growth in secondary porosity in the carbonate strata or of the replacement of carbonate.

4. Fluid inclusion data indicate that the mineralising fluids were extremely saline, with temperatures ranging from 60°C to 175°C (oil to gas window temperatures).

5. The ore galenas generally have a wide range in lead isotope composition and are commonly enriched in the radiogenic isotopes (J-type ore), thus indicating a complex diagenetic history.

6.6.1 Metal source rocks for MVT and McArthur type deposits

Wright (1990) described several potential metal rich source rocks which are widespread in sedimentary basins including Proterozoic sequences such as the Mount Isa Basin. Black shales (Holland, 1980; Meyers et al., 1992a), tuffs, igneous intrusions in basement and the sedimentary pile, and rift sequences in general (Rona, 1986), are the prime candidates. Some mineralised carbonaceous shales might not be simply source rock, but in effect low grade ore deposits, particularly if formed in a euxenic foreland sequence. Incorporation of these rocks into a later deformed basin could result in their being chemically stripped as source rocks.

Holland (1980) also concluded that the concentration of metals in organic-rich sediments owes more to chemical precipitation and to reactions with dead organic matter than to their incorporation in living organisms. Based on this observation, it seems that carbonaceous rocks, right from the time of earliest deposition, can act as sites for both base and precious metal precipitation if they are in contact with metal-rich fluids. Lyons and Berner (1992) described the carbon-sulphur-iron systematics of the uppermost deep-water sediments of the Black Sea as a pyrite producing system.

Rift sequences provide excellent metal source rocks which can be worked during subduction and collision to produce metallogenic deposits in a range of settings as illustrated by Hamilton (1973), Rona (1986), Kearey and Vine (1990) and Brimhall (1991) and modified to illustrate the Mount Isa Basin in Figure 6-3. Although black shales and intrusions commonly occur both in basement and the sedimentary sequence of the Mount Isa Basin, another likely source of metals in the basin was the anomalously-rich, rift phase volcaniclastic rocks deposited during the earliest basin formation. The Eastern Creek Volcanics have been considered a source of copper for the copper deposits in the Mount Isa Basin (Wilson et al., 1985) however, the data of Wilson et al. also shows anomalous levels of lead and zinc which may have sourced other base metal deposits.

6.6.2 Hydrodynamics in foreland basins

Within basins, both lateral and vertical migration is possible (up and down in veins, faults and fractures, plus horizontally within permeable zones). Fluid movement occurs due to elevation and geopressure but possibly is also due to eustatic sea level fluctuations, fluid density contrasts and thermal effects. In foreland basins, such as the last phase of deposition in the Mount Isa Basin, active gravitational pumping of brines probably occurred. Bethke (1990) presented a general model to describe fluid flow in asymmetric foreland basins based on hydrodynamic drive related to topography.

Klein (1991d) reviewed diagenesis and fluid movement in maturing basins emphasising the concurrent nature of the processes. This suggests the possible existence of long-standing hydrodynamic flows resulting in diagenesis, petroleum migration and mineralisation.

Understanding fluid hydrodynamics is especially important in a faulted asymmetric basin such as the northern Mount Isa Basin. It is known that at least some mineralisation in the Mount Les Siltstone occurs as a stratiform sequence in the northern flank of the basin (as predicted by fluid flow models), but the mineralisation also appears to be localised by major east-west faults and fractures such as at Lead Hill (discussed under Section 6.3.2). These faults may have acted as vertical conduits to laterally migrating mineralising fluids producing epigenetic deposits associated with stratiform mineralisation.

The major aquifers typically described in foreland basins have karstic porosity developed on the basal foredeep unconformity, and channel sandstones within the foreland sequence. This is best illustrated in North America where the major lead-zinc deposits occur on the continental side of the major Appalachian-Ouachita Orogen. Figure 6-4 illustrates the North American lead-zinc deposit distribution compared to the major hydrocarbon producing areas. Hoagland (1976) presented a diagram showing the Appalachian palaeoaquifer system which he considered to have acted as a migration pathway for MVT deposits (Figure 6-5).

Cathles and Smith (1983) calculated that flow rates of 300 to over 5000 times those that could be produced by normal steady state subsidence were required to produce MVT lead-zinc deposits. They considered that the ideal characteristics of a basin favourable to the formation of lead-zinc deposits were:

1. The basin should have contained abundant units of low permeability.

2. The internal structure should be complex and the average regional permeability should increase downward to facilitate downward movement of fluids through a basal aquifer.

3. The basin must have a stable margin to enable multiple pulses of metal bearing fluids.

4. The basin should have a thin but high permeability basal aquifer.

5. The basin should have structures that focus the dewatering fluids.

Each of the above characteristics are known or can be interpreted to have occurred in the northern Mount Isa Basin. Both faulting and brine migration are considered to have been triggered by orogenesis, and a thorough understanding of their relative timing is critical. Early thrusting, inverting rift-phase down-to-the-north normal faults, is thought to have occurred in the northern Mount Isa Basin (based on interpretation of seismic sections). This implies that long standing parallel tensional faults in the basin may have controlled metal-rich fluid migration and entrapment.

6.6.3 Brine compositions

Basin fluids, as typified by oilfield brines, are believed to have played a significant part in the formation of McArthur Type and MVT ore deposits. Gustafson (1981), reviewing McArthur River and many other deposits around the world, speculated that most sediment-hosted, stratiform deposits of both copper and lead-zinc formed early in the diagenetic history of the enclosing sediments, from brines derived from the sedimentary basin itself.

The chemical compositions of oilfield brines result from the interplay of several variables. These include the dissolved ions, salts, organic matter and hydrocarbons, plus reactions between these dissolved components and reservoir rock and its contained fluids. Connate water compositions and sedimentary rock types probably have the greatest influence on brine compositions, but each of these is variable depending on sedimentation type, ocean composition and temperature.

Collins (1980) observed that large quantities of dissolved gases are contained in metal-rich oilfield brines. Most of the dissolved gases are hydrocarbons; other gases, however, such as helium, carbon dioxide, nitrogen, and hydrogen sulphide are often present. The solubilities of these gases generally decrease with increased water salinities, and increase with pressure. The concentrations of dissolved hydrocarbons and other gases measured in drill stem tests from the Gulf Coast area of the USA (Buckley et al., 1958) generally increase with depth in a given formation and increase basinward with local variations. Near to some oilfields, the waters are enriched in dissolved hydrocarbon-rich gases. Over 2 m^3/m^3 has been observed at some locations.

Some oilfield brines contain a range of inorganic cation constituents in concentrations greater than 10 mg/L apart from sodium, calcium, magnesium, potassium, strontium, lithium and barium. These are discussed in Collins (1980). Examples of these are aluminium, ammonium, iron, lead, manganese and zinc.

Lead occurs in several oilfield brines around the world. Its solubility is limited primarily by the solubility restrictions of its sulphide and sulphate in reducing and oxidising systems. Lead is soluble in acetic acid and other acids, and it can be transported as the bicarbonate, which is a more soluble and stable form than the carbonate. Lead concentrations as high as 100 mg/L are found in some Jurassic oilfield brines in Mississippi (Carpenter et al., 1974). Metallic lead scale forms on some of the subsurface oil production equipment, causing severe oil production problems in the area.

The solubility of iron in oilfield brines depends on the iron compound involved, the amounts and types of other iron compounds in solution, the pH and the Eh.

Rocks commonly contain carbonates, hydroxides, oxides and sulphides of iron. Therefore, when the equilibrium is appropriate, iron can be dissolved or precipitated. Oilfield brines typically contain from trace levels to over 1000 mg/L of iron.

Carpenter et al. (1974) and Kharaka et al. (1987) described the chemistry of lead- and zinc-rich oil field brines from central Mississippi. Sverjensky (1984) described the geochemistry of an oil field brine as a model for an ore-forming solution. Barrett and Anderson (1975) described the solubility of sphalerite and galena in sodium chloride brines. The various accounts suggest low pH solutions were necessary to transport metals. One solution carrying metals as chloride complexes and sulphide simultaneously, appears unlikely.

Collins (1980) described some more important interactions of the chemicals in brines and between brines, petroleum and the surrounding rocks. The important interactions are:

1. Conversion of calcite to dolomite, which increases the calcium, strontium and barium concentrations in the brine while decreasing the magnesium and sulphate. Zinc and manganese may also be released.

2. Bacterial reduction of sulphate which reduces the sulphate concentration in the brine and increases carbon dioxide.

3. Formation of potassium and sodium aluminosilicates, which reduces the concentrations of potassium and sodium in the brine while increasing the concentration of calcium.

4. Ion exchange reactions between chemicals in the brine with chemicals in the rock e.g. alkali metals in the brine (e.g. Group I elements) and alkaline earth metals in the rocks (i.e. Group II element oxides).

Plimer (1992) considered circulating hydrothermal fluid through a sedimentary pile of volcanic, evaporite and clastic rocks to be responsible for ore genesis at Broken Hill. The passage of such a fluid, he considered, would have resulted in a supersaline tungsten-boron and halide-bearing mixed fluid, which upon sudden pressure change would have precipitated sulphides and other associated deposits.

Fluid inclusions give a snapshot of pore water compositions and temperatures at the inclusion entrapment time. Lisk et al. (1991) and Muir et al. (1985) have reported the results of fluid inclusion studies in the northern Mount Isa and the McArthur Basins respectively.

Muir et al. (1985) described the presence of saline brines trapped in healed fractures in barite and dolomite from Eastern Creek in the McArthur Basin. They also reported that some inclusions had been affected by later cracks and these were characterised by lower salinities probably representing depositional and vadose alteration conditions. The prime mineralisation associated, at least in part with the heated basinal waters of the Eastern Creek deposit, was iron sulphide.

Lisk et al. (1991) studied the hydrocarbon migration history and thermal history of Proterozoic carbonate rocks from the Doomadgee and Walford Dolomite Formations of the Fickling Group in the northern Mount Isa Basin, in borehole Amoco 83-4 (see Fluid Inclusion Studies, discussed under Section 5.4.3). The inclusions studied may be related the ore-forming or diagenetic reactions and thus represent migrating fluids within the basin at the time of ore deposition. In the local area, and within the borehole itself, grains of mineralisation are present.

Five different types of fluid inclusion were observed in the samples from the northern Mount Isa Basin and these are interpreted as having trapped three different pore fluids and mixtures of these pore fluids. One aqueous phase and two hydrocarbon phases can be discerned. The composition of the aqueous phase changed with time and this is indicated by differences in melting points. In addition, the composition of the liquid hydrocarbon phase also changed through time and this is indicated by differences in the fluorescence colour. The salinity of aqueous fluid inclusions during crystallisation of quartz overgrowths at 102°C has a range of 10 to >20 wt% NaCl equivalent (Lisk, 1991). During crystallisation of late carbonate cement at 125-135°C salinities were uniformly high at greater than 20 wt% NaCl equivalent. This suggests migration of hot concentrated brines after interaction with evaporites which mixed with local pore waters of lesser salinity. The change presumably reflects an increasing concentration of pore waters that migrated out of the northern Mount Isa Basin as diagenesis proceeded.

6.6.4 Origin and temperatures of brines

MVT deposits are widely considered to have formed by precipitation at shallow depths and low temperatures from transported, hot deep hydrothermal brines which commonly migrate through extensive karstic limestone aquifer systems. Collins (1980) concluded that oilfield brines in most sedimentary basins are probably genetically related to evaporites. Interstitial fluids in evaporite sequences may be expelled during compaction or the evaporite minerals may be leached by circulating ground waters.

Cathles and Smith (1983) described the thermal constraints on the formation of MVT deposits. They reported temperatures of precipitation from ore fluids in the range of 100 to 150°C at depths less than 1 km below the surface. Muir et al. (1985) concluded that the number and very large size of the base metal deposits in the McArthur Basin indicate that large volumes of hydrothermal fluids, and a large sulphate source, were involved in their formation. Muir et al. therefore suggested that basin-derived connate and/or surface water sources were involved in the formation of at least the larger deposits. Indicative fluid temperatures of 170 to 200°C were estimated based on organic matter colouring described as light to mid-brown. Pressure-corrected trapping temperatures in barite (95-138°C) and in vein dolomite (158-168°C) were reported.

Fluid inclusion temperatures refer to the time of crystallisation of diagenetic minerals and specifically to the time of closure of the inclusions. By contrast, organic matter maturation indices such as reflectivity, Tmax and colouration indicate the maximum temperature to which the rocks have been subjected. This is particularly so in some major Irish lead-zinc deposits where regional metamorphism has overprinted the deposits, but failed to breach fluid inclusions within diagenetic cements (Associate Professor L. H. Hamilton, pers comm., 1993).

Inclusions from the Doomadgee Formation at 121.3 m from drillhole Amoco 83-4 in both quartz overgrowths and carbonate indicate a mean homogenisation temperature of 102°C (Lisk et al., 1991). For Type B carbonate the mean is 125°C. Quartz overgrowths from the Walford Dolomite at a depth of 406.4 m in drillhole Amoco 83-4 give a mean of 102°C while euhedral quartz produced a mean temperature of 131°C. Carbonate-contained inclusions from the Walford Dolomite indicated a mean temperature of 126°C. Some high temperature values not incorporated into the means, were interpreted as inclusions which have trapped mixtures of aqueous liquid and gas and do not provide valid indications of the temperature of closure of the inclusions.

Temperatures at which the brine and metal-rich source rock interact are more speculative, however based on the thickness of the sedimentary pile in the Mount Isa Basin (about 15 km), and a foreland geothermal gradient of 30°C per kilometre and ambient temperature of 25°C, a nominal temperature of about 450°C is suggested. Speculation by Solomon and Heinrich (1992) that high heat producing granites may be necessary to produce ore forming fluids appears unnecessary. Their conclusion that ore-forming fluid flow was probably initiated by continent-scale extensional basement fracturing also seems unlikely in view of the foreland basin setting of the base metal host sedimentary rocks.

The results of the reflectance work from the Bowthorn Block drilling in the northern Mount Isa Basin are presented under Section 5.4.2, Source rock. Because the reflectivity can be directly related to the temperature to which the sample has been subjected, it is possible to recognise the movement of high temperature fluids through the sequence at the stratigraphic level of the C seismic horizon. The presence of mesophase bitumen in the sample from drillhole Argyle Creek-1 indicates the rock reached a temperature over 350°C (using the guideline of Gize, 1989). Mesophase in the northern Mount Isa Basin is developed along with zoned bitumens which are interpreted to be the result of incomplete hydrothermal maturation, and suggest several phases of hydrothermal transport. Although Gise also stated that fluid inclusions sometimes indicate lower temperatures than 350°C these could easily be due to later (or earlier) thermal overprinting, as with the Irish lead-zinc deposits, rather than the influence of geological time as he suggested.

6.6.5 Timing of brine movement

Muir et al. (1985) described the stratigraphic controls on the disseminated mineralisation at Eastern Creek. The mineralisation deposited there occurs only below the pre-Roper Group unconformity, implying that it may be older than basal Roper Group time. By contrast, in the northern Mount Isa Basin lead-zinc mineralisation is reported as high in the stratigraphy as the South Nicholson Group (Carter and Zimmerman, 1960). At Century, mineralisation also occurs within brecciated zones in the overlying Cambrian limestones implying that late remobilisation may obscure the picture. It seems unlikely that primary basin mineralisation extended into the Phanerozoic Era.

Lisk et al. (1991) considered hydrocarbon migration in the northern Mount Isa Basin occurred simultaneously with crystallisation of breccia cements over a minimum of 40 Ma and involving oils of different maturities and a methane gas phase. Migrating oils may have been displaced by gas from reservoirs deeper in the depocentre of the basin. The timing of the trapping of the hydrocarbons is not well constrained. If the mineral cements recrystallised at maximum burial depths as suggested by the consistency between modelled and measured maturations, then migration probably occurred between 1400 and 1000 Ma (Lisk et al., 1991). This seems very late. The higher permeability associated with fracturing and the trapping of different oils suggests the breccia and fracture zone has been a focus for fluid flow and that hydrocarbons have migrated from a range of depths and source maturities out of the basin.

Lisk et al. (1991) summarised the sequence of fluid migrations in the northern Mount Isa Basin as follows:

1. Pore waters of intermediate to high salinity were trapped during crystallisation of initial quartz overgrowths.

2. Migration of pore fluids with high concentrations of dissolved methane and a separate methane gas phase occurred.

3. Oil with cream fluorescence (under violet and ultraviolet excitation) and gas were trapped during crystallisation of euhedral quartz breccia cement.

4. Yellow and blue fluorescing oils (under violet and ultraviolet excitation) and methane gas migrated during crystallisation of clear carbonate infilling vugs. The carbonate crystallised from pore waters that had variable salinities and this suggests a mixed origin for these hydrocarbons.

5. Yellow and blue fluorescing oils and methane gas continued to migrate during the crystallisation of vein carbonate at a high angle to the bedding in the 121.3 m sample and carbonate cement in the 406.4 m sample. The pore waters had uniformly high salinities.

Plimer (1992) considered that the timing of brine movement at Broken Hill was related to sudden deepening of the region associated with an increase in the rate of clastic and chemical sedimentation and an elevation of the geothermal gradient. Using the basin model presented in this thesis, syntectonic formation is favoured for the ore deposits at Century and Mount Isa. They were probably deposited in undeformed areas ahead of the frontal thrust during the foreland phase of basin deposition. Century formed in the Lawn Hill Formation towards the top of the shallowing upward cycle of foreland phase deposition. The progressive cannibalisation that characterises foreland basins is such that syngenetic exhalative, syn-diagenetic, post-compactional epigenetic and syntectonic epigenetic deposits, as described by Large (1991), may each have formed within different parts of the Carpentarian Superbasin at the same time.

6.6.6 Migration

The movement of mineralising fluids within a basin follows the same basic hydrodynamic laws as migrating ground water or oil (Bethke, 1990). The presence of evaporites and shales within the sequence introduces the additional complications of variations in fluid density and episodic dewatering. Nevertheless, it is possible to reconstruct hydrocarbon migration pathways in undeformed areas such as the Bowthorn Block, and this information should also enable the prediction to be made of areas prospective for McArthur Type or MVT deposits.

There are only two likely migration possibilities for transporting metals from the deep basin to the site of deposition. The potential metal transporting agents are aqueous brines (with the metals moved as carboxylic acid complexes, sulphur complexes, or chlorides) or organic petroleum phases (where tetrapyrrole metal complexes may form). Manning (1986) noted the extreme solubility of lead acetate in aqueous solution and that it is really metals such as vanadium and nickel which consistently prefer the organic phase. Because petroleum generation and migration would most likely have occurred before metal generation (which may require higher temperatures), transport of metals as inorganic complexes seems to be the most probable mechanism. On the other hand, the matter of the sulphur source required for the precipitation the metals probably involved the early petroleum migration phase or independent bacterial generation at shallow depths.

6.6.7 The sulphur source

Understanding the sulphur source is critical to base metal precipitation. Brines are known to have been present in the northern Mount Isa Basin because of the work of Lisk et al. (1991). Oilfield brines commonly contain both dissolved metals and hydrogen sulphide gas. Collins (1980) discussed the sulphur-oilfield brine association. Sea water contains 900 mg/L of sulphur as sulphate, and subsurface oilfield brines contain from none to several thousand milligrams per litre. The amount of sulphate in a brine is influenced by bacterial activity and by the amount of calcium, strontium and barium present. If these three cations are present in relatively high concentrations, the amount of sulphate present in the liquid phase will be low. However, some brines containing high concentrations of magnesium and low concentrations of other alkaline earth metals may contain high concentrations of sulphate.

Hydrogen sulphide, often found in oilfield waters, is commonly formed by anaerobic bacteria, but can also be produced by chemical reaction of methane and anhydrite at elevated temperatures. One such bacterial species is *Desulfovibrio desulfuricans*, which obtains its oxygen from sulphate ions, causing them to be reduced to hydrogen sulphide. Trudinger (1981) reported that kinetic studies of sulphate reduction in anoxic marine sediments confirmed that sulphide accumulations equivalent to those in several major stratiform ores could be generated biologically. Jowett (1992) outlined the role of organic matter and methane in sulphide ore formation in the Kupferschiefer copper-silver deposits of Poland. He concluded that methane reacted with anhydrite to form calcite and hydrogen sulphide which precipitated copper sulphides in traps akin to petroleum bearing structures sealed by impermeable carbonates. The deposits are characterised by relatively flat spill point level ore/country rock contacts.

Collins (1980) noted that the Eh of subsurface oilfield brines is usually somewhat reducing, and the sulphur species in such environments can include hydrogen sulphide (H_2S), sulphite (SO_3^{2-}) and thionates ($S_4O_6^{2-}$). It is likely that other forms of sulphur are also present in some brines. The temperature, pressure, Eh, pH, and other constituents in solution all influence the types of dissolved sulphur that occur in oilfield brines.

Turner (1992) recognised that euxinic waters are H_2S-bearing and largely limited to stratified restricted basins. The foreland basin model proposed for the Mount Isa Basin in this thesis, suggests similar restricted basin settings may have occurred at various times during the history of this basin. Collins (1980) considered sulphur in surface waters usually occurs in the form (S^{6+}) complexed with oxygen as the sulphate anion SO_4^{2-} . The conversion of oxidised sulphur to a reduced form commonly involves a biogenic process, and such a reduction may not occur unless bacteria are present.

Both one and two fluid models have been proposed to account for sulphur at the site of metal sulphide deposition. Wright (1990) described three basic transportation/precipitation models although the first is considered unlikely due to the special conditions required for metals and aqueous sulphide to be moved in the same fluid at equilibrium. Two fluid precipitation mechanisms are discussed by Beales (1975) and Anderson (1975). The three models described by Wright (op. cit.) were:

1. **Metals and sulphide transported together in the same fluid.** In this case metal precipitation may occur by reaction with the host rock, a rise in pH, a temperature drop, or decrease in stability of chloride complexes due to fluid mixing (or possibly CO_2 escape).

2. **Metals transported in sulphate-bearing fluid.** In this situation trapping may occur by sulphate reduction by a variety of mechanisms.

3. **Metals transported in a low concentration sulphide fluid.** Here trapping can result from, mixing with hydrogen sulphide-bearing solutions (two fluid model), replacement of iron sulphides, and thermal degradation of organics.

The presence of early formed pyrite associated with the Mount Isa lead-zinc deposit (Neudert, 1983) suggests the primary availability of sulphur in the ore depositional environment. Schieber (1991) described the origin of sandstone-hosted disseminated lead-zinc mineralisation in pyritic shale horizons of the Mesoproterozoic Newfoundland Formation in Montana. The mineralisation there was porosity controlled and independent of formation of the pyritic shales suggesting excess sulphur was present. In the northern Mount Isa Basin, both bacteria and evaporites were present indicating two potential sulphur sources were available for metal precipitation.

6.6.8 Traps

Physical precipitation

There is general agreement that most metal deposits in the Mount Isa Basin were formed contemporaneously with basin filling during the Palaeo- to Mesoproterozoic. The major deposits commonly follow sedimentary layers, with graded bedding, varves, and scour structures etc., indicating that the sulphides were commonly precipitated in syngenetic to early diagenetic settings.

Because fluid temperatures were above boiling point (probably 150 to 250°C) sufficient water depth or burial depth was required to prevent boiling which would have resulted in extensive disruption of the sedimentary layers. Turner (1992) considered that formation of stratiform deposits requires the coincidence of stratified euxinic ocean conditions along with an exhalative hydrothermal system, but metal precipitation from basinal brines commonly occurs in shallow buried porous rocks.

Unlike MVT deposits which are commonly found in karstic breccias (Ohle, 1985), the deposits of the Mount Isa Basin are stratiform, interbedded with carbonaceous shales. The intimacy of interbedding is particularly apparent at Century (Waltho and Andrews, 1993). Only minor remobilisation to form epigenetic deposits in Cambrian limestones and the northern Mount Isa Basin sequence itself is observed around Century. Similarly to most MVT deposits, all the significant metal deposits within the Mount Isa and southern McArthur Basins are contained within the passive margin and foreland sequences.

The northern Mount Isa and southern McArthur Basins contain three well described giant lead-zinc deposits. These are Lady Loretta, Century and HYC. Each deposit is contained within a syncline today, but the structural setting at the time of deposition is unclear. All the deposits are located near major faults (Carlton Fault at Lady Loretta, Termite Range Fault at Century, and Emu and Western Faults at HYC) though there is no obvious genetic relationship. For example, the Emu and Western Faults have huge unmineralised inter-ore breccias derived from their eastern sides (Dr M.D. Muir pers. comm., 1993). As all deposits occur in basin areas exhibiting only moderate local structuring, quite possibly they formed in these synclinal traps. This genesis may relate to the high density of the basinal brines which transported the mineralisation, analogous with, but opposite to, a hydrocarbon trap.

Chemical precipitation

Meyers (1992b) outlined the role of organic matter in bacterial and thermal mineral precipitation. Oxidation of organic matter commonly influences the deposition of ore minerals by the reduction of metal salts and this is believed to have occurred in the Mount Isa Basin and the Carpentarian Superbasin. Plate 14 (f) is a SEM image of metals which have precipitated within gas window source rocks in the McArthur Basin. Plate 14 (g) is a reflected light microphotograph of metals (a chemical analysis indicated the presence of iron, copper, lead and zinc) associated with high reflectivity pyrobitumens in drillhole Desert Creek-1. Expulsion of oil from the kerogen produces "micropores" or voids, probably filled with gas (e.g. Plate 14, e), which appear commonly to act as sites of metal precipitation (Dr M. Glikson pers. comm., 1992). Both galena and sphalerite were commonly observed associated with overmature kerogens in the McArthur Basin.

Trudinger and Cloud (1981) considered that the presence of "saddle" dolomite was evidence against "biogenic" lead-zinc mineralisation (of the type described by Ramm and Bella, 1974), forming in many carbonate host rocks. "Saddle" dolomite indicates relatively high temperatures (up to 150°C) and is perhaps formed along with sulphides during inorganic sulphate reduction. No "saddle" dolomite has been recognised in the northern Mount Isa Basin. Bubela (1981) described an experimental "early" epigenetic model for sulphide band formation that may be applicable to McArthur River and Mount Isa Basin type deposits by providing a mechanism for the early precipitation of metals from saline waters. Ferguson and Burne (1981) described Spencers Gulf in South Australia as a modern analogue for a similar diagenetic ore genesis system.

The solubility and precipitation of metals from hot waters up to 300°C emanating from a little under a kilometre in depth in geothermally active areas, is the subject of a report by Yardley (1991). When water escapes upward, either naturally or in a borehole, the drop in pressure causes it to boil spontaneously or flash. High pressure geothermal pipes form scale rich in a range of elements including copper, silver, gold, zinc and lead.

Yardley (1991) noted that sulphide complexes transporting gold have been proposed as a mechanism for the origin of many other types of gold deposit. Gold is much more soluble as gold-sulphide ligand complexes than in its elemental state. At Cloggau, near Dolgellau in Wales, gold is found in quartz veins, but only where they cut through Cambrian black shales. The shales are black because of organic matter or "graphite" spread throughout the rock. Within the vein quartz, there are fluid inclusions, largely composed of water, but some contain methane as well. The gold is interpreted to have been transported upwards as sulphide complexes in water. When this hot water met the black shale at around 300°C, it produced methane. The methane then separated out from the water, taking the hydrogen sulphide with it in the same way that hydrogen sulphide separates into the steam fraction when hydrothermal fluids boil. As in the geothermal fields, the loss of reduced sulphur makes gold sulphide complexes unstable and triggers precipitation.

Yardley (1991) pointed out that ideas on how gold is extracted from rocks, redistributed and then concentrated by natural processes, are being revolutionised by simple, elegant ideas from solution chemistry, combined with astute geological observations. These geothermal systems provide an illustration of the chemical processes that may have precipitated the ores in the northern Mount Isa Basin.

The presence in the northern Mount Isa Basin of metal sulphides associated with organic matter suggests that the sulphide could have precipitated by the action of organic carbon acting as a reductant on a single hot metal-sulphur carrying fluid. It is also possible that the metals were syngenetically related to the alginite. Either of these mechanisms could account for the presence of mesophase and pyrolytic carbon and the disseminated metal sulphide-organic matter association common within the basin. Abiogenic reduction of sulphate, as noted by McQueen and Powell (1983) in relation to the Pine Point lead-zinc deposit, or substitution of sulphur from hydrogen sulphide-rich gas as proposed by Anderson (1991) for Mississippi Valley base metal deposits, are also possible precipitation mechanisms for the large Proterozoic base metal deposits of the Mount Isa Basin and the Carpentarian Superbasin of the Proterozoic of Australia.

Stratigraphically controlled mineralisation

"Shale" hosted deposits occur on a large scale throughout the Mount Isa Basin. Century in the northern Mount Isa Basin and McArthur River in the southern McArthur Basin both contain high levels of carbonaceous matter and possibly degraded hydrocarbons. Cellular organic matter is intimately associated with McArthur River ore (Hamilton and Muir, 1974). It is therefore possible that sulphurous gas produced locally could have been capable of forming a sulphide trap.

Taylor (1971) suggested that the Broken Hill deposit probably contained much more carbonaceous matter than at present, making it quite similar to the Mount Isa region. Carbon as graphite, is present, but rare today at Broken Hill because of reaction with water during regional metamorphism. Based on carbon isotope data, Hamilton (1965) concluded that the graphite in the Broken Hill lode is most probably biogenic in origin. It is therefore possible to speculate that carbonaceous shales may have acted as both metal source rocks and even provided the necessary reducing conditions to precipitate the ore at Broken Hill.

King and Thomson (1953) considered that before metamorphism, the Willyama Block sedimentary rocks contained simple conformable lead-zinc deposits of the type seen elsewhere in the world. Knight (1953) found that the lead-zinc lodes at Mount Isa have the same strike and dip as the shale beds containing them, and in plan they are arranged en echelon, more or less parallel to the strike of the fold axes. This is very similar in style to many petroleum stratigraphic traps.

The South Nicholson Group of the northern Mount Isa Basin contains the Train Range Ironstone which has an organic-rich zone at its base. This carbonaceous unit contains only minor lead-zinc mineralisation, but the association with porous oolitic ironstone and highly carbonaceous rock could provide the basis for a major chemical trap.

Structurally controlled mineralisation

Many of the deposits of the Mount Isa Basin are associated with faults and may have been due to late phase remobilisation as postulated for the Silver King deposit near Century in the northern Mount Isa Basin by Blake (1987). Conversely, discordant mineralisation may represent feeders, but there geometries and stratigraphic levels make this interpretation unlikely.

At a regional scale, relatively undeformed ore is present at McArthur River. Increasing levels of structural deformation are observed at Century, Lady Loretta, Hilton, Mount Isa, Dugald River and Cannington. Highly deformed mineralisation occurs at Broken Hill. This structural and regional metamorphic variation is considered an overprint **not** related to base metal ore genesis.

Kettler et al. (1992) interpreted gold precipitation in sedimentary rocks to be due to sulphidation of ferrous iron. They considered that this occurred when fault controlled hydrothermal fluid encountered reactive Fe^{2+} in diagenetic siderite. Siderite is present in small quantities in Mount Isa Basin copper-gold deposits such as Selwyn (Kary and Harley, 1990). The presence of siderite at Selwyn could have enabled gold precipitation from structurally controlled deep basin fluid migration as a result of syn- to post-depositional deformation.

6.7 GENETIC LINKS OF MCARTHUR TYPE (NORTHERN MOUNT ISA BASIN) AND MVT SEDIMENT HOSTED STRATIFORM LEAD-ZINC DEPOSITS TO OIL FIELD BRINES AND HYDROCARBONS

Large (1983) considered sediment hosted lead-zinc deposits formed through exhalative mineralisation. Typical features of the process include, delicate lamination of the stratiform sulphides to the massive sulphide ore, metal zonation and cross-cutting country rock (footwall) mineralisation and alteration that is interpreted as representing the discharge vent for the movement of mineralised groundwater. It is widely thought that mineralised basin waters have played a major role in the genesis of many of these ore bodies. The exhalative model requires that tensional fault systems are feeders and that mineralising fluids moved through the sediments during diagenesis while they were still waterlogged and relatively uncompacted. Precipitation of the ore components is believed to have occurred by boiling or mixing. Metals are transported in a hydrothermal solution as soluble chloride complexes. If these chloride complexes become unstable, the free metal ions react with available sulphide ions to form metal sulphides. Mechanisms for changes in stability include, decrease in temperature, decrease in chloride concentration, increase in sulphide concentration and increase in pH. A temperature induced stability change may be caused by adiabatic boiling of the solution before exhalation or simply by the mixing of the hydrothermal solution with seawater after exhalation.

Turner (1992) recognised the two modern analogues of exhalative model where sulphidic sediments may have accumulated in a brine pool caused by the ponding of discharged saline hydrothermal fluid within a sea-floor depression (e.g. metalliferous sediments in the Atlantis II deep, Red Sea) or from a hydrothermal plume as found at ocean ridge hydrothermal vent sites. Other lead-zinc deposit models listed by Large (1991) were syn-diagenetic, epigenetic- "post-compaction" and epigenetic- "syntectonic".

Similarities between oil field brines and inclusion fluids and the spatial association of some hydrocarbons with sulphide accumulations (Baines et al., 1991) have prompted some to suggest that genetic affinities occur between hydrocarbons and carbonate-hosted lead-zinc deposits (e.g. Sverjensky, 1984; Anderson, 1991). Although there are different opinions concerning metal sources and causes of mineral precipitation, it is widely accepted that these carbonate-hosted ore deposits, like petroleum and natural gas accumulations, are the result of a normal sequence of events in an evolving sedimentary basin (Kyle, 1983).

Dunsmore and Shearman (1977) observed that many workers had noted that MVT orebodies occupy special positions with respect to the limestone basins which contain them. They are commonly found around the basin margins, or on "highs" or other structures, where they would have lain along the natural migration paths of formation brines and other fluids. Some writers have stated that the orebodies commonly occupy what might otherwise have been stratigraphic, structural or facies oil traps, albeit somewhat leaky ones (e.g. Anderson, 1991).

The association of hydrocarbon with lead-zinc orebodies is quite common. Dunsmore and Shearman (1977) observed:

"Solid and liquid hydrocarbons are commonly encountered in ore zones, and solid liquid and gaseous hydrocarbons are frequently present as inclusions in the ore minerals themselves. Extreme cases were encountered in some mines of the Tri-State District of the USA, where records show that oil and bitumen were present in such quantities that the ore had often to be washed with kerosene before it could be milled. In one mine viscous oil dripped from the roof onto the men working below, while tar from another mine was so abundant that it was used for roofing purposes by local builders. Indeed, in one instance a shaft had to be abandoned because of an influx of thick oil at the ore horizon".

At the other end of the spectrum, sphalerite and galena have been encountered in significant amounts in borehole cores of the oil- and gas-bearing reefs in the Devonian of Alberta and northern British Colombia, where it has been said that some carbonate oil reservoirs would be mined for lead and zinc if they occurred closer to the surface. Some North Sea oilfields also contain significant lead-zinc mineralisation in association with oil and gas (Baines et al., 1991). Montacer et al. (1988) described the relationship between lead-zinc ore and oil accumulation processes in the Bou Grine lead-zinc deposit in Tunisia, suggesting a close association.

The genetic link between tectonism, hydrocarbons and lead-zinc mineralisation is very clear in basins such as the Arkoma in the USA (Leach and Rowan, 1986) where dry gas generation appears to have formed at temperatures beyond the range of lead-zinc precipitation or preservation. But there is good evidence that lead-zinc mineralisation can occur at a range of temperatures close to the oil generation window.

Gize (1989) discussed the importance of determining the active or passive role of organic matter in ore genesis. Macqueen and Powell, (1983) demonstrated that the bitumens at Pine Point lead-zinc field, Northwest Territories, in Canada, are less mature than those in the nearby oilfields associated with fluid inclusion temperatures of 50 to 100°C. The hydrocarbons which range from malleable to hard, insoluble material, in the Pine Point lead-zinc field, appear to have developed in response to the mineralising event which occurred at a temperature range from below to within the oil window. Marikos et al. (1986) also described solid insoluble bitumen in the Magmont West Orebody, Southeast Missouri as having formed late, after mineralisation.

Etminan and Hoffmann (1989) concluded from biomarker fluid inclusion studies in the Canning Basin, that Pb-Zn mineralising fluids were associated with hydrocarbons generated at depth within the basin. They showed that hydrocarbons trapped in fluid inclusions in sphalerite and gangue minerals did not generate from local source rock and are epigenetic with respect to the host rocks at the site of mineralisation. They could not determine if the hydrocarbons were in place before the mineral precipitation or if they migrated along with the Pb-Zn.

Anderson (1991) hypothesised a sulphate-reduction plus mixing concept for ore precipitation and Mississippi Valley Type mineralisation in Southeast Missouri. To show a plausible mass balance between sulphate, possible reductants, and sulphide ores, and a mechanism for mixing the reduced gas (H_2S) with the metal bearing fluid, it was necessary to focus on the associated gases (mostly methane). The methane and associated hydrogen sulphide was generated (liberated) from the organic matter in the host carbonate rocks during thermal maturation caused by heat from the hydrothermal solutions. This possibility provided a realistic mass balance as opposed to the trivial amounts of oil and bitumen found in close association with the ores.

Another aspect of the work of Anderson (1991) relates directly to the association of Mississippi Valley Type deposits and oil field brines. He concluded that Mississippi Valley lead-zinc deposits do not form from the oil field brines with which they are associated i.e. they are not formed by processes related to basin or petroleum formation. Rather they form from brines expelled from deformed basins migrating to shallow immature areas. The heat they supply by advection and conduction in these shallow sequences induces "artificial" or non-burial organic maturation. This conclusion is similar to the conclusion of Crick (1992) who described anomalously high maturation indices adjacent to the base metal mineralisation in the HYC deposit in the McArthur Basin.

Many authors have described the connection between basin deformation and the emplacement of mineralisation-bearing brines presumed to have formed MVT deposits. Clendenin and Duane (1990) described the regional focussing of the MVT fluids due to different orogenic events as producing different deposit types. Kesler et al. (1989) described the evolution of mineralising brines in the east Tennessee Mississippi Valley-type ore field showing that calcium-rich brines initially deposited fluorite while later sodium-calcium-rich brines deposited the ore field sphalerite. Ravenhurst and Zentilli (1987) described the buildup of excess pore fluid under an evaporite seal resulting in massive hydrofracturing and fluid expulsion to produce lead-zinc-barite deposits of Fundy/Magdalen Basin of Canada.

Oliver (1986) used a regional approach to determine the relationship of hydrocarbon fields, MVT deposits and orogenic belts. He observed that gas, oil and then lead-zinc occur with increasing distance from the thrust belt out into the stable craton. Clearly each deposit type forms ahead of the north American Phanerozoic thrust belts and deposits are not found within the orogenic belts themselves. Kesler and van der Pluijm (1990) described the timing of MVT mineralisation in relation to Appalachian orogenic events and particularly noted the early emplacement sphalerite before any host rock deformation.

The basin deforming processes Anderson (1991) described could easily be the same as those that create foreland basins. It is therefore apparent from the work undertaken during this thesis, that the processes that mature oil source rocks and migrate oil maintain relatively uniform geothermal gradients within basins. Processes that produce base metal deposits are vigorous and disrupt basin geothermal gradients by the expulsion of large volumes of hot deep basin fluids to quiet shallow-depth depositional sites.

Whether the mass balances for ore precipitation require a brine-gas reaction as opposed to a brine-oil reaction can be assessed only with very detailed knowledge of each individual deposit. The proposition that the mineralising brines are in some way fundamentally different to those responsible for petroleum generation and migration is difficult to sustain. While metal precipitation conditions may require hot brines to migrate to cool, shallow, immature parts of a basin, these hot brines must undoubtedly mature, migrate, and possibly even crack hydrocarbons during their journey, dependant upon the brine temperature. It is therefore probable that oilfield brines and metalliferous brines are the same fluid, only the geothermal equilibrium, hydrodynamic flow regimes, metal contents, and sites of precipitation of metals compared to the structural entrapment of oils and gases, are different. These simplified envelopes of generation and entrapment for hydrocarbons, lead, zinc, copper and gold are presented schematically in Figure 6-6.

The association of lead-zinc and hydrocarbons was found in the case of the McNamara Group within the Riversleigh Fold Zone except that maturity is too high for liquid hydrocarbons to have been preserved and most gas originally present has probably leaked. Despite this, reports and descriptions of bituminous materials containing volatile hydrocarbons in lead-zinc mines within the Lawn Hill Formation do exist (Ball, 1911). This is additional to the organic matter associated with the major deposits of the Carpentarian Superbasin. The temperatures of crystallisation of MVT and McArthur type deposits are commonly little more than that required to mature hydrocarbon source rocks, as illustrated by Wright (1990; modified in Figure 6-6), and the presence of lead and zinc deposits and overmature source rocks only emphasises the extensive generation of hydrocarbons within the McNamara Group.

6.8 CONCLUSIONS

The major base metal ore deposits of the Carpentarian Superbasin are probably syntectonic, but were mostly deposited in undeformed areas ahead of the frontal thrust during the foreland phase of basin deposition. Cannibalisation of foreland sedimentary rocks plus the earlier basin sequences, suggests that the range of deposit types, from early to late, may each have formed within different parts of the Carpentarian Superbasin at the same time. Only in the northern Mount Isa Basin and the Bowthorn Block in particular (plus parts of the McArthur Basin), are the original stratigraphic superposition of the sequences, and the syn-depositional basin structures, sufficiently intact to allow unambiguous interpretation.

6.8.1 Consanginuity

The time and space relationship of ore deposition in the northern Mount Isa Basin and the Carpentarian Superbasin generally, strongly suggest that the ore genesis process was an integral part of the basin evolution. Mineralisation sourcing, structural deformation, and signatures as described previously, demonstrate kinship in the form of similar mineralisation styles, basin structural settings, trace elements, age and formation mechanisms for the major stratiform deposits throughout the Carpentarian Superbasin. Basin cannibalisation implies there were only timing differences related to the various geographic locations of the major base metal deposits. Indeed the common aspects of all the major deposits implies that despite their wide range of metamorphic overprints observed today, they all formed by a similar process.

Because at least two regional aquifer systems were probably operational within the Mount Isa Basin, deposition within at least two preferred stratigraphic levels probably occurred (e.g. Lady Loretta and Lawn Hill Formations). These comprise the section at the top of the basal foredeep unconformity (commonly marine transgressive black claystones and siltstones overlying shallow water carbonates) and shelfal unconformities (where deep water channel sandstones interdigitate with fine grained turbiditic claystones and siltstones).

For example, the Century deposit (the largest lead-zinc deposit known in the northern Mount Isa Basin) and probably the Mount Isa deposit both occur stratigraphically near the top of the foreland sequence where the depositional environment was shallow. This is one of the few levels in the basin where many tuffs occur (tuff layers are present in both deposits). By comparison, the Lady Loretta, McArthur River and Dugald River deposits (and even the Walford Creek system in the Mount Les Siltstone) all occur within or immediately above the thick shallow water carbonates of the passive margin phase.

In short, the major stratiform deposits of the Carpentarian Superbasin formed by similar processes in the same basin, but at more than one stratigraphic level and probably at slightly different times as the orogenic belt developed from south to north.

6.8.2 Plate tectonic models

Plate tectonics can produce catastrophes, but it is not a chaotic system. It appears to be the prime basin forming mechanism since the beginning of the Proterozoic, at least. Ocean basins have a life cycle which can be used to approximate the duration of rifting and development of passive margins and basin evolution.

The Arkoma-Appalachian-Allegheny Basins of the southern and eastern USA are probably the best described analogues of the Mount Isa Basin. Hoagland (1976) produced a diagrammatic regional cross-section through the Appalachian Basin (Figure 6-5). The section shows rift-drift phase carbonates overlain by deep-water foreland clastic sedimentary deposits which acted as a regional seal to Pb-Zn rich brines which are considered to have precipitated the massive MVT Tri-state lead zinc deposits.

The relative lack of MVT deposits within the Mount Isa Basin, except for Redbank in the southern McArthur Basin, Coxco near HYC and Bulman (Walker, 1981; Wall and Heinrich, 1990) is difficult to explain in terms of the likely reservoir system at the level of the basal foredeep unconformity. Perhaps Phanerozoic reefal carbonate build-ups are fundamentally different in structure having higher porosities, permeabilities and profiles (Hamilton, 1973). Pelechaty and James (1992) suggested that dolomitised Proterozoic calcretes exhibit many aspects similar to Phanerozoic deposits. On the basis that no petroleum was found below the basal foredeep unconformity, and that drilling failed to encounter any significant preserved reservoir, possibly the better aquifers were associated with the shelfal unconformities where the Century deposit in the northern Mount Isa Basin, occurs today. Alternatively, perhaps the hydrodynamic system physio-chemistry occluded porosity and permeability in the platform carbonates before the migration conditions for hydrocarbons and metals could be established. The data on this point are still insufficient to fully reconstruct the fluid migration systems in the basin.

6.8.3 Ore deposition and base metal plays

Because the northern Mount Isa Basin fits so closely into a Wilson Cycle model it is a logical step to test the many aspects of such a model in the way that the petroleum drilling campaign tested the basic sequence stratigraphy. By knowing the timing of structures, the basic plumbing system and locations of the "metal shows" in the area, shallow drilling to systematically test many different types of fault and stratigraphic metal traps throughout the northern Mount Isa Basin is now possible.

The known major stratigraphic levels of mineralisation would make up the primary targets -- the top of the platform carbonate sequence (above and below the level of the basal foredeep unconformity), and the lower part of the molasse sequence (where shelfal unconformities truncate deep water channel sandstone aquifers which interdigitate with fine grained turbiditic claystones and siltstones). In addition, the density of occurrence of major deposits, the large number of metal "shows" or "prospects", and the enormous potential for other structures within the northern Mount Isa Basin, and the Carpentarian Superbasin regionally, suggest that much exploration potential remains to be tested.

Now that the northern Mount Isa Basin sequence stratigraphy has been deciphered, an obvious play is to test the other areas of the Carpentarian Superbasin for McArthur Type ore bodies e.g. Georgetown Block, East Kimberley Bungle Bungle Dolomite etc., in stratigraphically equivalent sequences, if they are present and can be recognised.

7 EVOLUTION OF THE MOUNT ISA BASIN HYDROCARBON AND METALLOGENIC PROVINCES

The Mount Isa Basin was initiated by continental breakup of the cratonised Murphy Inlier and its equivalent basement sequences. The simplified sequence stratigraphy and economic geology are illustrated in Figure 7-1.

Deposition on the pre-rift basement unconformity produced a rift sequence composed of volcanic and volcaniclastic sedimentary section rich in a wide range of metals (Pb, Zn, Fe, Mn, Cu, Ag, Au, etc.) typical of modern spreading centres. Some hydrocarbon source rocks were probably also deposited at this time. A small amount of hydrocarbon and metal mobilisation and redistribution probably also occurred, but in insignificant amounts compared with later. The basin at this time experienced a tensional stress regime with down-to-the-north faults and significant nearby volcanism associated with rift thermal plume or hot spot. Several heat centres coalesced as spreading continued, creating an east-west rift zone. A high geothermal gradient existed throughout this phase of basin development.

Following the initial rift, the basin underwent a passive margin drift phase. This developed on the breakup unconformity at the top of the rift sequence. Widespread development of shallow water carbonates with minor evaporites characterised the sedimentary sequence during this phase of basin evolution.

During the drift phase, the basin was located in warm palaeolatitudes enabling the deposition of carbonates to take place with interbedded black shales rich in organic matter. Typical of basins during this phase of their development, the Mount Isa Basin probably experienced a relatively cool geothermal gradient. As the approximately 3000 m thick carbonate sequence accumulated, progressive burial of the rift sequence probably had little effect on either the organic precursors of the hydrocarbons or metals within the system. As diagenesis proceeded and passive margin deposition attained its maximum thickness, the oil and basin fluid migrations continued slowly.

Subsequent collision of the rift-drift Mount Isa Basin phases resulted in the formation of an Andean scale mountain chain and the peripheral foreland phase of deposition in the basin. Plate tectonic reconstructions suggest the possibility that the colliding plate was the Wopmay Orogen and retroarc Slave Province of northern Canada. At the time of continental collision the suture and orientation of the axis of the basin was probably east-west with northern Canada approaching from the south (Figure 3-37). Based on the ATP 423P seismic interpretations, the Murphy Inlier began to develop as a peripheral bulge with the basal foredeep unconformity forming on the most northerly platform and rift sequences. (The Murphy Inlier does not appear to be an extension related core complex). Progressive formation of the superimposed foreland basin resulted in remobilisation of both metals and hydrocarbons contained in rift related source rocks and possibly pre-existing traps. This resulted in the degradation and escape of some hydrocarbons by cracking to gas and leakage up faults and fractures. Widespread metal and hydrocarbon migration ahead of the frontal thrust probably produced the major existing metal deposits at this time and degraded much of the then existing trapped oil. The structural evolution from passive margin to foreland phases resulted in progressive inversion of early growth faults and cannibalisation of existing basin along with parts of the newly produced foreland basin phase. During this period, convective heat transfer through aquifer systems probably disrupted the existing, essentially vertical geothermal gradient, redistributing both heat and fluids containing the dissolved metals in the hot basin depths and hydrocarbons nearer the cool margins. As hydrocarbon generation and migration is thought to have taken place at lower temperatures before metal mobilisation, progressive faulting, squeezing out of fluids ahead of the frontal thrust, and hydrodynamic flow could easily have produced several periods of mobilisation with many complex interactions. The formation of syngenetic (exhalative and diagenetic) and epigenetic (post-compactional and syntectonic) ore deposits all probably took place throughout the foreland phase of both the Mount Isa Basin and Carpentarian Superbasin evolution.

With the cessation of foreland basin development, the major Wilson Cycle which produced the basin was complete. The hydrodynamic regime within the basin probably continued to operate but as compaction, diagenesis and regional metamorphism reached their peak, the major basin processes undoubtedly waned.

Subsequent collision from the east with dextral strike-slip movement on the Mount Gordon Fault demarcating the northern Mount Isa Basin from the Carpentarian Superbasin was the final major deformation event in the northern Mount Isa Basin's history. Most of the structures from this collision are observed in the southern Mount Isa Basin. Some fluid movement may have recommenced at this time, but it is doubtful if major hydrodynamic systems were again established.

Erosion and breakup of the Carpentarian Superbasin by the Warburton failed rift and partial coverage by the Georgina Basin sag then produced the Mount Isa Basin as defined in this thesis. Continued breakup during the opening of the Palaeozoic Amadeus Basin followed by eventual closure and foreland development, resulted in negligible further deformation to the northern Mount Isa Basin outcrop. Cratonisation of the basin was complete by this stage and most intraplate stresses were simply transmitted through and beyond the solid basin.

Breakup continued during low β, sag style "failed rifting" which produced the Cooper Basin and partially buried the Mount Isa Basin. The development of the Mesozoic Carpentaria and Eromanga Basins followed by the development of the Cenozoic Karumba Basin continued the burial of the Mount Isa Basin. Tertiary erosion and peneplanation through to today has resulted in the exposure of the more deeply buried parts of the southern Mount Isa Basin and parts of the northern Mount Isa Basin. Apart from erosion at the level of the basal

Mesozoic unconformity, the Bowthorn Block has experienced little structural deformation since the conclusion of sedimentation in the basin.

Plate 15 (a, b and c) comprises three views illustrating the structural attitudes in the Cloncurry Orogen, Riversleigh Fold Zone and the Bowthorn Block today. The great contrast between the rocks in each of these three areas was the key to the basin analysis undertaken in this thesis and it governs the exploration techniques applicable to each area.

As widespread degradation and leakage of hydrocarbons as pyrobitumen veins etc., is present today south of the Elizabeth Creek Thrust in the northern Mount Isa Basin, there is little hope of locating even gas in that area. Both oil and gas shows exist within the northern part of the Bowthorn Block, but attempts to find commercial hydrocarbons have been unsuccessful to date. The possibility exists that in the less mature area at the extreme northern edge of the Mount Isa Basin and in the McArthur Basin, some preserved hydrocarbons remain to be discovered. "Metal shows" are present throughout the northern Mount Isa Basin with the major deposit of Century having been recently discovered in the Riversleigh Fold Zone. Prospectivity for metals in the northern Mount Isa Basin is currently excellent although the chance of locating commercial hydrocarbons in the area is less promising.

8 CONCLUSIONS

The major aim of this thesis has been to determine a basin model and define the Mount Isa Basin. This has been achieved and tested by the acquisition of seismic and drilling exploration data within ATP 423P. In the light of the new data the terms "Mount Isa Basin" and "Murphy Inlier" are proposed as more appropriate descriptions of the Proterozoic rocks which crop out in the Mount Isa region of northwest Queensland. Not only do these more accurately describe the situation, conceptually they allow for a deeper understanding of the geology of this region. Although a name change may seem a trivial issue to some people, the basin context for the old Proterozoic rocks at Mount Isa is a paradigm shift applicable to both the rocks at Mount Isa and many Proterozoic rocks throughout Australia.

Existing descriptions such as "Mount Isa Inlier", "South Nicholson Basin", "Lawn Hill Platform", "Murphy Tectonic Ridge" and "Mount Isa Orogen", for the reasons presented above, less clearly describe the area and it is recommended their use be discontinued. The new structural terms recommended to describe the basin deformation zones are, from north to south, "**Bowthorn Block**", "**Riversleigh Fold Zone**" and "**Cloncurry Orogen**". The basin is divided into two geographic areas, the northern Mount Isa Basin and the southern Mount Isa Basin separated by the Mount Gordon Fault. This simple change resolves the serious existing problem where lithostratigraphic and structural concepts overlap.

The hydrocarbon potential of the northern Mount Isa Basin was tested as part of this thesis study. Despite the low volumes of hydrocarbons discovered, the petroleum geology of the Bowthorn Block of the Mount Isa Basin was an important test of the preservation potential and generative capacity for early matured Proterozoic hydrocarbons. The success possibility of the structures tested and the additional potential of the basin were commensurate with the high risks of a grass-roots exploration play. This study of the Mount Isa Basin has also made a useful contribution to the understanding of the petroleum geology of Australia and the hydrocarbon exploration of Palaeo- to Mesoproterozoic sequences in general.

The basin model which enabled me to define the Mount Isa Basin was also tested as part of the hydrocarbon exploration program. The play which tested the basin required drilling over two kilometres thickness of foreland phase turbidites to intersect the shallow water platform carbonates within structural closure. Such a venture is not undertaken lightly and it was gratifying that the model based originally on seismic and outcrop data, was confirmed by the drilling results, despite the disappointment of not locating hydrocarbons in economic quantities.

Application of the seismic technique to the northern Mount Isa Basin has been shown to be very successful despite the high velocities of the rocks. Use of this technique enabled me to recognise the sequence stratigraphy and interpret the basin's evolutionary history. The presence of greenstones at Mount Isa, serpentinites at Broken Hill and possibly Georgetown agree with the suggested late phase foreland orogenic plate margin settings. Combined with the other data from this thesis, Proterozoic plate tectonics appears to be the most feasible mechanism to account for the variability and style of the Mount Isa Basin and the Carpentarian Superbasin. Using the plate tectonic approach for both generation and breakup of the superbasin Broken Hill mineralisation in the Willyama Block plus several other regions appear to have genetic links to Mount Isa style mineralisation.

The Mount Isa Basin hydrocarbon and mineral provinces appear to be closely correlated. Hydrodynamic transport of oil, gas, and metals in the basin can be related to maturation and basin deformation, though each commodity may have been produced, deposited, and even destroyed (in the case of hydrocarbons) by different events. Ore genesis in the Mount Isa Basin appears to be related to foreland basin tectonism and cannibalism of source rock produced in the rift phase of the basin. Zn, Pb, Ag, Cu and Au were probably stripped from source rocks at progressively higher temperatures, possibly at the same time, but in different parts of the Mount Isa Basin. Despite this, their entrapment windows appear to have been quite different. To reach favourable physio-chemical deposition sites the metals must have been preserved in solution until they reached areas still immature for petroleum generation. Zn- and Pb-bearing solutions appear to have migrated through aquifers where there was sufficient hydrodynamic head to enable rapid transport to a site for concentrated deposition. Therefore, it is possible to interpret a deformed basin hydrodynamic model for fluid flow in the region. These solutions may also have also migrated up fractures and faults producing many of the small epigenetic deposits in the region. Cu- and Au-bearing solutions probably utilised fracture conduits or fault planes to move from deeper source areas in the deformed basin to their final sites of deposition. Compared with the Mount Isa Basin, rifting conditions in "failed rift" basins (rift-sag systems), were either weaker or they prevailed for a shorter time. "Failed rift" basins generally exhibit initial metal-poorer rift phases and less intense hydrodynamic regimes which result in greater metal dispersal and an apparent lack of major economic metal sulphide deposits.

The Mount Isa Basin is only part of a larger, plate tectonic scale, Proterozoic system referred to in this thesis as the Carpentarian Superbasin, very similar to the Phanerozoic orogenic system of eastern USA, the Ouachita-Appalachian Orogens stretching from Newfoundland to Mexico. The Carpentarian Superbasin is believed to extend to Broken Hill and beyond. The true beauty of studying the Bowthorn Block of the Mount Isa Basin, apart from any economic potential it may have in its own right, is that it represents the same basic ingredients that went into the well done scrambled eggs at Mount Isa and the burnt scrambled eggs at Broken Hill.

9 APPLICATIONS AND SUGGESTIONS FOR FURTHER WORK

Petroleum exploration in ATP 423P has enabled me to produce a detailed regional geological study of the northern Mount Isa Basin, a previously little understood sedimentary sequence. The major economic application, however, is in assessing the prospectivity of the region for hosting massive stratiform sulphide deposits. In particular, the seismic data and photogeological mapping can be used to identify principal fault zones and possible morphological traps for sulphide accumulations. Field mapping and well information tied to seismic data has led to the identification of sedimentary sequences which probably host massive sulphide mineralisation. Further studies to generate base metal plays based on the new interpretations in this thesis will help determine the precipitation sites of stratiform sulphide deposits within the region and the stratigraphic controls on metal sulphide precipitation.

Continuing analysis of the seismic and drilling data generated to date will enable further understanding to be made of the evolution of the Mount Isa Basin. Detailed burial history models based on maturation profiles, and better control on the unconformity and disconformity surface levels resulting from detailed analysis of the recent petroleum well information in the basin, will be possible. This thesis originated from a search for preserved commercial hydrocarbon accumulations in the Palaeo- to Mesoproterozoic Mount Isa Basin. Although economic oil and gas were not discovered the possibility for their existence remains. Both the extreme northern Mount Isa Basin edge and the McArthur Basin to the north offer further potential for success.

This thesis provides an example of the development of a detailed economic basin analysis. Modern exploration requires integrated basin analysis by teams of specialists. No other methods are currently known that can supply the data required for basin, system, play and prospect analysis. Many other poorly understood Precambrian basin systems remain to be studied in a similar way. The Proterozoic is equivalent to about three Phanerozoic time-spans. Therefore, several plate tectonic scale basin systems probably existed in Australia and widespread opportunities exist for basin analysis.

The application of the seismic technique to Proterozoic basins is most appropriate despite the high velocities of such rocks, provided intense deformation and high metamorphic grades are not present. Structures identified on the Bowthorn Block seismic data appear to be related to basin architecture with late east-west compression. Deformational stress directions within the Mount Isa Basin are interpreted to be: north-south tension, north-south compression and later east-west compression. This agrees with the compressional stress directions determined by Bell (1991) for the area near Mount Isa. From the seismic data it can be concluded that much of the early tensional faulting was accommodated on pre-existing planes of weakness in the Murphy Inlier and that the above order of deformation represents only the average stress regimes which deformed the basin. Although the last stress direction was east-west compression, existing fault planes and block rotation resulted in local areas of tension and oblique deformation which occurred simultaneously. The capacity of the seismic technique to provide data suitable for high quality structural analysis in both local grids and at a basin scale, greatly improved the understanding of the early thin-skin and synsedimentary deformation in the northern Mount Isa Basin. Basin seismic analysis (0 to about 6 seconds) is capable of profoundly influencing interpretations in other similar old basins and possibly through seismic windows in the more deformed parts of the Mount Isa Basin itself.

The Carpentarian Superbasin now awaits detailed analysis and precise definition. An important aspect is in the link between Mount Isa and Broken Hill. Reconciling detailed deformation in the each area will be a difficult task. Despite this, basin deformation at Broken Hill and Mount Isa were probably quite similar although more intense at Broken Hill.

10 CONTRIBUTIONS TO GEOLOGY AND GEOLOGICAL PHILOSOPHY

The objectives addressed in this thesis are significant to both the hydrocarbon and minerals exploration industries. It is ironic that this work was conducted in a region which was not previously recognised as a basin. To understand the boundaries of the Mount Isa Basin it was necessary to interpret a larger picture enabling the recognition of the Carpentarian Superbasin. To define the Mount Isa Basin it was necessary to separate structural and stratigraphic concepts which overlapped in the existing literature, finally producing a clear picture of the detailed stratigraphy and structuring within the Bowthorn Block, and the regional stratigraphic correlations and structuring in the basin.

Ore genesis in the Mount Isa Basin appears to be related to foreland basin tectonism and cannibalism of source rock produced in the rift phase of the basin. This model may be generally applicable to other basins of various ages, particularly analogues associated with Mississippi Valley deposits in North America. An important geological idea in the context of exploration in a range of basins is the relationship of hydrocarbon to mineral provinces. This study showed that the hydrodynamic transport of oil and gas, or metal-rich brines, in many basins probably occurred despite each commodity being produced and deposited by different events. Hydrocarbon and base metal provinces therefore appear to be closely related in foreland basins produced in collisional plate tectonic settings.

To understand many aspects of the Proterozoic sequences of the world, it is obvious from this study that a good knowledge of Phanerozoic basins and plate tectonics is required. A rift/passive margin/peripheral plate tectonic model appears to be the best to account for the variability and style of the Mount Isa Basin. A plate tectonic model is certainly the most plausible for the equivalent age basins in north America and probably for all basins of this age. From this it is possible to infer that Proterozoic Earth processes (geological systems, atmosphere and even climate) were very similar to Phanerozoic systems.

Evidence from this work on the Mount Isa Basin suggests that these rocks did not form any kind of Proterozoic shield in the strict sense, only an old basin. The concept of metallogenic epochs is also not supported by this study of the Mount Isa Basin. It appears there was just an old basin and metallogenic systems similar to the many Phanerozoic examples cited in the references.

This new basin model suggests that ore genesis in the foreland sequence may have more in common with Mississippi Valley Type mineralisation than previously supposed (brine transport along major aquifers from the basin deeps and early epigenetic depositional styles). An old term for the Mount Isa Basin was the Mount Isa Geosyncline (Hill and Denmead, 1960) and, of course, the original geosynclinal concept defined by Dana (1873) was based on the Appalachian Foreland Basin, one of the best analogues for Mount Isa. With this model it is possible to apply petroleum exploration ideas to mineral exploration.

Research and exploration are unique industries pitted primarily against nature seeking undiscovered natural resources or unknown processes and techniques. There is no right way to undertake research or exploration. On this basis, the current study, which is a description of an exploration research effort, should be judged on its ability to improve the knowledge of the Proterozoic rocks at Mount Isa in terms of both data and interpretation. What this thesis is about is an understanding of the northern Mount Isa Basin and the Dallenbach figure shown as Figure 10-1 attempts to encapsulate the idea (look at Figure 10-1, and try to interpret this before looking at Figure 10-2). You have to see the big picture to make sense of the small parts of basins in which exploration is carried out! And once the understanding is achieved the original data in all its details, is transformed and filled with new meaning and opportunities.

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APPENDICES

APPENDIX 1

Seismic processing parameters

The data was processed for Comalco Aluminium Limited over the period December 1990 to August 1991 incorporating some data from field processing work and interpretation by E. Bos and B. McConachie undertaken during the final stages of the processing.

During the 1991 seismic processing a mild coherency filter was added to the processing stream described below.

PROCESSING REPORT

BY : E. Bos

Seismograph Services Limited

1990 Burketown Seismic Survey

Block ATP 423P Queensland

TRIALS

Processing trials were performed to determine optimum parameters including Spherical Divergence Correction, FK filter, Deconvolution, Residual Statics as well as various Post Stack processes.

PROCESSING

Initially, the data was demultiplexed, written to SEG-Y format and converted to minimum phase.

FK Filter

After a stack trial, it was decided that this data would benefit from the application of an FK filter. A full fan Hamming tapered FK filter with full cut at 1930 m/s was designed from trials.

Gain

Spherical divergence correction was chosen from a gain trial and a simple time variant gain was chosen with each sample being multiplied by the time at which it occurred. Trace header information was applied to the data at this stage.

Deconvolution

For deconvolution trials, sufficient data was edited off the line to give 80 full fold CMP's. Various trial deconvolution operators and windows were applied to these panels and the data was sorted and stacked using approximate velocities obtained from a velocity analysis performed in the area. Surface consistent residual statics were applied as well as a post stack filter of 10-12 to 80-90 Hz. Performance of the deconvolution operator was checked using an autocorrelogram. A three window predictive deconvolution was chosen because the optimum gap length varied with depth. A 100 ms operator length was found to be sufficient for the data and a three window deconvolution with gap lengths of 16, 24 and 36 ms respectively, were chosen from the trial.

For the western lines (around Connolly Valley) where data quality was generally poor, a 2 domain (shot and receiver) deconvolution was tried and found to improve data quality. Because of the extra processing effort involved, this option was only used on those lines that required it. For the two domain, a single design window operator of 100 ms length and with a 16 ms gap was chosen from trial panels.

Sort

After deconvolution, the data was sorted into 30 fold CMP gathers and a 1000 ms AGC was applied to re-balance data levels.

Statics

Statics did not present much of a problem in this area. A trial was performed using Green Mountain Geophysics first break statics package, but the results were not significantly different from using simple elevation statics with weathering and replacement velocities calculated from upholes and interpolated between upholes.

NMO

At this stage the first round velocity analyses were performed. Consistent velocity stacks were used as these give a broader range of velocities to examine at any given depth; this is useful when there is not an accurate idea of what velocities to expect. Velocity analyses were performed every 2 kilometres. NMO correction was applied and a time offset post NMO mute was designed from examining NMO corrected gathers on a trial line. The same mute was used for the entire area.

Residual Statics

After the initial NMO correction, residual statics were calculated using an iterative automatic surface consistent residual statics program. The general approach is to solve the residual source and receiver statics based on relative shifts between members of a CMP. Time shifts of all members of a CMP relative to a model trace are determined. These picked shifts are used to compute a surface consistent set of source and receiver statics using an iterative method. Three sets of statics are derived, the first with a stacked, static corrected CMP as the model, the second using as the model the trace in the CMP with the best correlation from the first time shift estimation and the third using a model derived by picking the most surface consistent of the first two sets of statics and applying those to the CMP before stacking. This is also the model used to derive the initial shifts for the next CMP on the line. The final statics used are the most consistent of the three sets found. This process resulted in a small continuity improvement with statics of the order of 4-10 ms being found.

NMO

Second round NMO analyses were performed on the residual static corrected CMP's. Multi velocity stacks were once again used and one was performed every kilometre. Post NMO mute performance was checked on each line by displaying muted and unmuted NMO corrected gathers at each velocity analysis location and a revised mute was picked for this stage. Once again a single mute function was found to be useable for the entire area. NMO was found to fluctuate fairly rapidly in the area over a range of 200-300 metres per second.

Mute

An initial mute was chosen from NMO corrected CDP gathers and used for the whole area. A surgical mute designed to remove dipping noise trains in the CDP domain was found to further improve data quality in the region of interest.

Residual Statics

CDP trim statics were used for the second round of residual statics. In this process a pilot trace is generated by stacking a specified number of CMP's which are tapered about the central CMP. Each trace in the central unstacked CMP is then cross correlated with the pilot trace. The cross correlations are resampled to 1 ms to allow the statics to be picked to the nearest millisecond. The cross correlation is examined and after a number of checks a shift is picked and stored in the trace header for later application. Once a CMP is completed a new pilot trace is generated centred about the next CMP. A specified window, usually centred about the data of interest, is used for the above process to enable statics to be picked in a good signal to noise ratio area of the trace and so that the area of interest is improved maximally. To improve the performance of the pilot trace the input data is flattened to approximately align the same event on neighbouring CMP's. This pass resulted in some improvement in the data although again only small statics of the order of 5 ms or less were found.

Stack

The data was stacked into nominal 30 fold CMP's. Each live sample in the stacked trace was divided by the square root of the number of live samples contributing to that stacked sample.

POST STACK PROCESSING

Migration

Lines 90BN-01 to 90BN-08 as well as part of line 90BN-10 were wave-equation migrated using the Finite Difference method designed for steep dips (up to 45°) and lateral velocity variation. This method divides both time and space up into discrete samples. The time sampling interval, 't', is the same as the original sample interval of the data (i.e 4 ms). The X direction sample interval is taken to be the same as the CDP interval. The depth interval dZ is taken as a multiple, N of the sample interval multiplied by the velocity at that point (N*V*t). N*t is called the depth interval parameter, tau, and in this version it is a constant so that dZ varies with velocity. For this data tau was set at 40 ms. To reduce wrap around an end effects, 100 dead CMP's were padded at each end of the data prior to migration and removed after migration. Testing was performed to determine the optimum migration velocity which was found to be 90% of the stacking velocity.

FX Filter

A complex Weiner Prediction Filter performed in the FX domain was applied. This has the effect of reducing incoherent noise and has good results on this data set.

Bandpass Filter

A very mild 2 window post stack filter was chosen from low cut and high cut trials.

Scale

Time Variant AGC was used on all stacks. The window size was linearly interpolated from 200 ms length at 400 ms on the section to 800 ms length at 1700 ms.

Display

Final stacks were displayed at a large scale of 15 cm per second and 8 traces per cm (1:10 000). A small scale stack was produced by applying a 2:1 trace sum and displaying at 10 traces per cm and 15 cm per second giving a final scale of 1:25 000.

APPENDIX 2

MEMORANDUM

REF:	Q.1.3	
DATE:	7 August 1990	
TO:	P W Stainton	14/Brisbane
FROM:	B A McConachie	14/Brisbane
COPY:	K B McDonald	14/Brisbane

SUBJECT: **RESULTS OF A DECISION ANALYSIS TO DETERMINE THE MOST SUITABLE DRILLING TECHNIQUE FOR ATP 423P.**

Attached is a Kepner Tregoe style decision analysis undertaken to compare conventional and slimhole drilling techniques in the South Nicholson Basin/ Lawn Hill Platform sequences in ATP 423P.

The result is the product of a team effort in which Michael Barlow, John Dunster, Roger Meaney, Arie Schaap and myself participated. Most points were thoroughly canvassed from a range of perspectives and surprisingly perhaps, consensus was reached on every significant issue. The technique enabled a complex decision on which most people had a pet opinion based on aspects of the problem, to be considered in a rational and comprehensive manner. This enabled a conclusion to be drawn with which everyone is in basic agreement.

The actual technique used by Kepner Tregoe was modified by categorising the weighted issues and reweighing them to make the comparison as meaningful as possible. The categories into which the 51 items were placed were: petroleum evaluation of the area, costs and safety. The great number of cost items meant that the original analysis was biased towards costs. This made absolutely no difference to the answer to two decimal places! Perhaps this result indicates the robustness of the technique and that the answer is broadly based and not merely related to the cost differential.

The final result, I believe, can be described as conclusive. The points score indicates a 20% difference in favour of the conventional drilling technique. In addition, the risk analysis demonstrates that there are no high probability/high seriousness risks associated with conventional drilling. In contrast, eight probable and serious risks were identified for slimhole drilling.

B A McConachie

DECISION STATEMENT:	TO SELECT A DRILLING TECHNIQUE FOR ATP 423P
Two Alternatives are available – Conventional and Slimhole	
MUSTS	
1.	Be capable of drilling to the required depth.
2.	Be approved by the JV partners.
3.	Provide conclusive data for petroleum evaluation purposes (DST's, core, wireline log and complete).
4.	Approved by Department of Resource Industries (safety, rig selection, work program).

				CONVENTIONAL		SLIMHOLE	
WANTS	Category*	Weight	Normalised Weight*	Score	Points	Score	Points
1. Lowest possible drilling cost (day rate with pipe)	C	10	3	6	18	10	30
2. Lowest mobilisation cost	C	8	3	6	18	10	30
3. Lowest cost of road works	C	7	2	6	12	10	20
4. Lowest standby rate	C	4	1	7	7	10	10
5. Safest while drilling	S	8	6	9	54	10	60
6. Safest while cutting core	S	8	6	10	60	9	54
7. Safest while retrieving core	S	8	6	10	60	6	36
8. Safest while testing	S	10	7	10	70	9	63
9. Maximum drill crew experience	C/S/P	5	3	10	30	7	21
10. Availability of experienced company man	C/S/P	8	4	10	40	7	28
11. Minimise differential sticking	C/S	9	5	10	50	6	30
12. Minimise key seating	C/S	5	3	8	24	10	30
13. Minimum casing and cementing costs and ease of supply	C	2	1	10	10	6	6
14. Ability to cope with lost circulation	C/S	8	4	10	40	9	36
15. Geological experience in old rocks	C	2	1	7	7	10	10
16. Best quality sample information	P	8	8	6	48	10	80
17. Minimum field support by Comalco	C	2	1	10	10	7	7
18. Should be convertible to producing well as easily as possible	C	6	2	10	20	6	12
19. Avoid drilling deviation	P/C	7	5	10	50	4	20
20. Minimise service company numbers	C	3	1	6	6	10	10
21. Minimum cost of water requirements	C	3	1	4	4	10	10
22. Maximum Comalco experience	P/C	2	1	9	9	10	10
23. Avoiding drillpipe washout	C/S	8	4	10	40	5	20
24. Minimise risk of downhole drilling problems (wedge offs, dropped core, faulty calipers, dropped cones)	C	8	3	10	30	6	18
25. High rate of penetration	C	6	2	10	20	5	10
26. Minimum number of loads	C	3	1	5	5	10	10

				CONVENTIONAL		SLIMHOLE	
WANTS (continued)	Category*	Weight	Normalised Weight+	Score	Points	Score	Points
27. Availability and reliability of wireline logging tools	P	8	8	10	80	7	56
28. Minimum mud requirements	C	2	1	6	6	10	10
29. Obviate need for crane	C	3	1	9	9	10	10
30. Shortest possible rig-up/down time	C	5	2	10	20	3	6
31. Most reliable drillstem test	P	9	9	10	90	6	54
32. Easiest possible drillstem test	P/C	4	3	10	30	5	15
33. Maximum service company experience	P/C/S	3	2	10	20	5	10
34. Ease of dealing with sloughing shales	P/C	2	1	10	10	4	4
35. Ease of dealing with evaporites	P/C	4	3	7	21	10	30
36. Selection of drill bits to cater for wide variations in lithology	C	5	2	10	20	7	14
37. Ability to decrease hole diameter to overcome drilling difficulties	C	6	3	10	30	5	15
38. Ability to perforate casing	P	8	8	10	80	7	56
39. Minimum site earthworks	C	1	1	8	8	10	10
40. Ability to convert to water bore	C	1	1	10	10	8	8
41. Time loss due to condition and circulate	C/P	3	2	10	20	8	16
42. Availability of models for predicting fluid dynamics	C	2	1	10	10	3	3
43. Core transportation and storage	C	1	1	10	10	2	2
44. Ease of monitoring expenditure	C	1	1	8	8	10	10
45. Ability to detect small oil shows	P	7	7	4	28	10	70
46. Suitability for conventional ditch gas sampling apparatus	P	1	1	10	10	7	7
47. Spare mud pump(s)	C	6	2	10	20	4	8
48. Spare drive engine	C	6	2	10	20	8	16
49. Fuel consumption	C	2	1	8	8	10	10
50. Avoid spin out	C/S	6	2	10	20	5	10
51. Widest possible selection of contractors and rigs	C	7	2	10	20	3	6
				TOTAL	1 350.00		1 127.00

Table 1. MUSTS AND WANTS

*Categories C = cost
P = petroleum evaluation
S = safety

+Normalised weights - see Table 2

WEIGHTS	Safety (S)	Cost (C)	Petroleum Evaluation (P)
Initial ratio	57.2 (or 10)	152.2 (or 26.6)	57.2 (or 10)
Desired ratio	7	8	10
Divide weight by to achieve normalised weight	1.4	3	1
Actual ratio	7.8	12.5	10

Table 2. WEIGHTS AND NORMALISED WEIGHTS

The purpose of normalising the weights for each of the wants was to prevent the costs from dominating the analysis, due simply to the large number of cost items which were able to be identified. The theoretically desired ratio could not be easily achieved in practice because it was not practical to reduce the weights for items with a weight factor of only one. Each cost item considered to be of sufficient importance to be included in the analysis is probably worth a weight score of at least one. The actual weights ratio finally achieved were therefore slightly biased towards cost followed closely by petroleum evaluation then safety.

The requirements to be achieved by either drilling technique can be listed as follows:

1. The drilling must evaluate the area to achieve the primary exploration objective.

2. The joint venture should not spend too much, but the cost difference between the two techniques is not great.

3. Each method would probably be quite safe, but the area has not been tested and therefore some risk will be involved.

Finally, the result of normalising the weights in this analysis made no difference to the relative scores of the techniques.

RISK ANALYSIS	SLIMHOLE		CONVENTIONAL	
	Probability	Seriousness	Probability	Seriousness
Standby delays could cause cost over run due to bad weather.	M	L	L	M
Delays due to bad ground.	M	M	M	L
Risk during gas test. Chances of conducting a gas test are low but consequences of failure are great.	M	H	M	M
Lost circulation can result in the loss of the well and even blowout.	M	H	L	H
Washouts can lose hole.	L	L	L	M
Drillstem test must work to enable full evaluation. Seats better in slimhole and easier to pick. Slimhole tool is less reliable and less commonly run.	M	H	L	H
Failure to provide adequate access to site for contractor.	L	M	L	H
Chances of mechanical or physical failure due to drill rig drilling near depth capacity.	H	H	L	M
Testing well near rig capacity.	M	H	L	H
Risk of wireline tool failure and no replacement.	H	H	L	H
Risk of failure to drill to target or reach total depth due to deviation along faults or inclined bedding.	M	H	L	H

Table 3. RISK ANALYSIS

For conventional drilling the medium probability/medium seriousness risk associated with gas testing will be reduced by using a good quality blow out preventer and regularly testing the unit. Regular drills will also be conducted to minimise the consequences of equipment failure.

Probability and Seriousness rated as H = high, M = medium, L = low

NOTES: WANTS

1. **Lowest possible drilling cost (day rate with pipe).** Approximately 25% of total cost. Slimhole $4800, Conventional $7900 (1988 costs).

2. **Lowest mobilisation cost.** Mobilisation is at least 17% for conventional and 10% for slimhole. Slimhole $96000, Conventional $197000 (1988 costs).

3. **Lowest cost of road works.** Somewhat lower percentage of total well costs than mobilisation. Slimhole requires smaller loads. A slimhole rig can be moved by 6 x 6 trucks, conventional rigs require prime movers.

4. **Lowest standby rate.** About 5% of well cost. Slimhole $4000 per hour, Conventional $6000 per hour. Both conventional and slimhole rates are 90% of day rate with pipe.

5 - 8. **Safest while drilling. Safest while cutting core. Safest while retrieving core. Safest while testing.** Cutting core is equivalent to drilling for a slimhole rig. All aspects apart from testing do not involve such great consequences. Slimholes can produce swabbing and induce a kick more easily. Slimhole gear is less robust. Flow from a well can be more easily detected in a slimhole, but procedures for controlling kicks in slimholes are less well tested.

9 & 10. **Maximum drill crew experience.** Availability of an experienced company man. The company man has great influence but the drill crew can effect running pipe and drilling rate. Few experienced slimhole company men exist because the technique has not been widely applied to oil exploration.

11 & 12 **Minimise differential sticking. Minimise key seating.** Slimholes are more prone to differential sticking. Key seating occurs only rarely with a slimhole.

13. **Minimise casing and cementing costs and ease of supply.** Casing and cement cost relative to total cost is about 10%. Slimhole casing and cement costs are more than conventional because of the requirement for deeper casing, more cement and special grades of cement.

14. **Ability to cope with lost circulation.** Lost circulation can lose a well. Slimholes can only cope with mild lost circulation.

15. **Geological experience in old rocks.** This is important because ATP 423P is a hard rock area but the limited experience can be overcome by careful planning.

16. **Best quality sample information.** Sample information is critical to evaluate a well. Chips are much less desirable than core but spot cores and sidewall cores would still be cut with a conventional rig.

17. **Minimum field support by Comalco.** Slimholes are more complex and require more support.

18. **Should be convertible to producing well as easily as possible.** Joint Venture Partners will rate this highly, but it is not critical to basin evaluation. Slimholes are difficult to convert and will only produce a small flow. It is possible that a slimhole will only be suitable for evaluation purposes.

19. **Avoid drilling deviation.** Slimholes will deviate more than conventional. Greater than 10° deviation in slimholes is possible and is more difficult to correct than in a conventional well. Comalco personnel must monitor drillers carefully.

20. **Minimise service company numbers.** Multitasking of personnel and utilising people to minimise travel costs and avoid nuisance value is essential for both drilling techniques. More people are required for conventional drilling but the drilling time is shorter.

21. **Minimum cost of water requirements.** Five fold increase in water requirements for conventional. Total water required for conventional well could be up to 5% of the well cost. Sufficient water can be obtained from Flying Fox hole in west with 500 m of fire hose and this would not be a substantial cost.

22. **Maximum Comalco experience.** Some experience with both techniques, but slightly more slimhole exposure.

23. **Avoiding drillpipe washout.** Conventional pipe upsets rub against the hole. Drilling in the Officer Basin resulted in one in five slimholes using 101 mm drillpipe washing out. Washouts are harder to detect in slimholes as slimhole drillpipe pressure is higher than in conventional drillholes. All pipe should be pressure tested before use and at regular intervals during drilling.

24. **Minimise risk of downhole drilling problems (wedge offs, dropped core, faulty calipers, dropped cones).** Potential long time delays can be caused. Shorter well time means less potential problems.

25. **High rate of penetration.** Average figures are given in the table below. The difference can be as high as double in favour of conventional rigs. This difference balances the relative day rate costs of the two techniques.

	Drill Rate m/day	
	Conventional	Slimhole
Spot to release	40.6	33.0
Spud to release	44.9	33.2

26. **Minimum number of loads.** Half the number of loads for a big slimhole versus a big conventional rig. At least 15 loads are required for any system.

27. **Availability and reliability of wireline logging.** For correlation and evaluation purposes good logs are essential. Previous slimholes often used inferior wireline logs. Good slimhole suites are now available but limited in supply. Wireline logs represent 13% of total well costs for conventional drillholes.

28. **Minimum mud requirements.** Mud costs and freight are the major components. The total is 7% of the cost for conventional wells. Conventional costs are 50% higher than slimhole. Slimholes may not need a mud engineer on site; conventional wells do.

29. **Obviate need for crane.** Crane lifting can be done in Mt Isa at no great cost or inconvenience.

30. **Shortest possible rig-up/down time.** Rig-up/down time can be 25% of the total well time. Slimhole rigs are inherently more complex to rig-up/down.

31 & 32. **Most reliable drillstem test. Easiest possible drillstem test.** Reliability is almost a must but ease is a cost saving with risk potential for failure. Inability to obtain or poor quality drillstem test data could invalidate the basic aim of petroleum evaluation of the area. Slimhole drillstem tests need 3½ inch pipe which must be carried in addition to the usual 101 mm.

33. **Maximum service company experience.** Mudloggers can be a problem in terms of slimhole experience. Few testers have worked with slimholes.

34. **Ease of dealing with sloughing shales.** Thin Carpentaria Basin cover means that this problem will be relatively minor but conventional wells have considerably fewer problems.

35. **Ease of dealing with evaporites.** The probability of encountering any evaporites is low. Slimholes have very small mud volumes and so it is easy to salt saturate the mud system. In addition, hydraulic pressure is lower behind bit in slimholes resulting in less formation washout behind the bit.

36. **Selection of drill bits to cater for wide variations in lithology.** Old rocks have more lithology variation than young rocks particularly in the carbonates. Conventional rigs may have more flexibility with wider bit selection available. A range of tricone and button bits as well as polycrystalline diamond facing is available for conventional rigs.

37. **Ability to decrease hole diameter to overcome drilling difficulties.** Could be necessary if a well needs deepening or problems occur. It can be very difficult to reduce drillhole gauge with an already slim hole.

38. **Ability to perforate casing.** This will be very important for full evaluation. Some potential problems for slimholes.

39. **Minimum site earthworks.** This is a low cost item and some earthworks are always necessary.

40. **Ability to convert to a water bore.** Public relations is of value. Slimholes require more complex completion in the form of narrower and more powerful perforating guns.

41. **Time loss due to condition and circulate.** Condition and circulate is less than 10% of any total well cost. This also effects evaluation potential of the well. Slimholes need more conditioning.

42. **Availability of models for predicting fluid dynamics.** None are available for slimholes as they are theoretically complex to model.

43. **Core transportation and storage.** This is a low cost problem mainly caused by the volumes of core produced by slimhole drilling. Conventional cores can be transported in any vehicle; a slimhole produces up to 25 x 2 ton pallets of core. Slimhole core transport costs can be as high as $40000/well. Core storage can be a major problem for slimholes.

44. **Ease of monitoring expenditure.** Relates to operation complexity which is greater for slimholes. The longer duration of slimholes means that potential cost blow out can be detected and appropriate action taken.

45. **Ability to detect small oil shows.** Small oil bleeds can be useful for evaluation and are best detected with core. Spot cores are available with conventional holes but the more the better.

46. **Suitability for conventional ditch gas sampling apparatus.** Small cost and the necessary modifications can be made.

47 & 48. **Spare mud pump(s). Spare drive engine.** Can lose a well in some circumstances if these are not available but each increases the number of loads. Both will be useful in this remote area.

49. **Fuel consumption.** The cost is less than 4.5% of a total well. Slimhole rigs are smaller and more fuel efficient. Conventional rigs use 2200 L/day as against 1000 L/day for slimhole rigs.

50. **Avoid spin out.** This can cause the loss of a well. The chances increase with depth and mud weight. Can only occur in slimholes.

51. **Widest possible selection of contractors and rigs.** The number of rigs and contractors reflects upon competitive costs. Very few slimhole rigs are available.

APPENDIX 3

Risk analysis in hydrocarbon exploration and ATP 423P

Basin risk

A 500 million barrel oil field can be considered economic anywhere in Australia. This would represent US$10 billion worth of oil with a development cost of perhaps US$100 million for a pipeline and offshore oil terminal somewhere north of Burketown. If one structure had been successful, a reasonable estimate for similar features would have been that at least ten others could have been found, indicating a possible potential of 5 billions barrels of oil or US$100 billion in oil revenue. This would have been achieved with little additional developmental costs. These figures are amazingly encouraging and do reflect the upside potential of the northern Mount Isa Basin, but they do not take into account the most important financial element in petroleum exploration, the risk factor.

Risk can be more influential in petroleum exploration than simple economic analysis. In many ways it cannot be quantified and yet makes great impact upon the assessment of any play or prospect. If we consider some grass-roots areas; for example, the onshore Carpentaria Basin contained targets of 1 to 2 million barrels (US$20 to $40 million at US$20 per barrel) which would be economic close to Weipa. The offshore Carpentaria Basin has targets of the order of 100 million barrels (US$2 billion), while the northern Mount Isa Basin had targets of 500 million barrels (US$10 billion). Each of these latter basins represented significant stand alone economic potential. The real difference between all the plays is the probability of success. The onshore Carpentaria Basin has always been very high risk style of play. The offshore Carpentaria Basin has moderate risk, the real hope being that source rock and maturity will be better within the Carpentaria Depression. Relative to these projects the northern Mount Isa Basin was high risk largely associated with the lack of identified and predictable reservoir in the sequence, and the frontier nature of the work.

An important aspect in any grass roots petroleum exploration program, such as was undertaken in the northern Mount Isa Basin, is to prove that oil may be present. This means that a purely technical success i.e. finding one barrel of oil, may sufficiently reduce the exploration risk so that a large field could be discovered later. Whilst this may be an important goal in frontier type exploration, it is difficult to justify on pure economic grounds. For example, the finding of one barrel of oil in an onshore Carpentaria Basin exploration well would have set in train a boom in offshore Carpentaria Basin exploration. This is the fundamental reason to maintain a rational exploration acreage exposure, to balance risks with potential rewards, to farm-in and farm-out to spread risks and to keep objectives clearly in focus. The drilling exploration program in the northern Mount Isa Basin was designed as a fundamental test both reducing prospectivity and leaving no significant remaining upside potential.

The high costs in petroleum exploration are not the development costs. Development costs can be carefully assessed once a discovery is made, on the basis of what has actually been found. The major cost in oil exploration is the finding cost. Importantly once a petroleum discovery has been delineated the finding cost, while of interest, is purely a sunk cost and has no further impact (apart from possible tax implications) upon the development. In this way, exploitation of a petroleum discovery depends almost entirely upon the development cost in relation to the value of the find and this can only be properly assessed when all the facts are known i.e. after the discovery well.

Finally, the economic considerations of the northern Mount Isa Basin must be considered. Prior to the 1992 drilling:

1. The basin was high risk but with high upside potential. Egilabria-1 potentially contained 200 BCF of gas or 20 million barrels of oil recoverable at the C horizon target level. The western portion of the ATP has enormous stratigraphic and combination trap potential not so different to analogues such as Prudhoe Bay (Selley, 1985) and East Texas (Levorsen, 1967).

2. Exploration in the ATP 423P block was low cost in terms of the reward potential that could be evaluated quickly.

3. Local markets for both gas and oil existed and will expand in the future.

4. No well had been drilled on a valid structure in this basin and a range of play types were present.

Basin, play and prospect specific risks

Harbaugh et al. (1977) described probability based Monte Carlo methods used to assess systematic exploration strategies for a number of basins. These work well for a large number of tests, approximately fifty, but don't take into account the number of plays and prospect types tested or indeed the validity of each test based upon, for example, seismic control.

Each prospect in the northern Mount Isa Basin as with any grass roots exploration area can be evaluated in terms of a risk-reward profile based upon both the potential of the individual structure, and its probable significance as a play type throughout the basin. As the database for the basin increases more detailed risk analysis can be employed based on the concepts outlined by Rose (1987), where specific aspects of each play are quantitatively assessed.

In grass roots basins like Mount Isa, Kepner-Tregoe style analyses (Kepner and Tregoe, 1981) are probably the most applicable to prospect ranking as dollar values of targets must take a secondary role to technical basin prospectivity assessment. In the final analysis a combination of economic and technical considerations was used to select the three drilling targets for the 1992 drilling campaign.

From the seismic data it seemed probable that Beamesbrook-1 penetrated a sequence similar to the highly carbonaceous Riversleigh Siltstone and Lawn Hill Formation. The Riversleigh Siltstone is interpreted as a deep water euxinic turbidite deposit which is overlain by, and interdigitates with the shallower water sandstones of the Lawn Hill Formation and South Nicholson Group. The upper part of the Lawn Hill Formation was not penetrated in the well and indeed no reservoir facies were encountered. Because of this complex local stratigraphy, identification of channel sandstone reservoir facies from seismic stratigraphy and lithofacies analysis, was very difficult.

On the basis of the Kepner-Tregoe analysis Egilabria-1 was considered the best target in the basin for the 1992 drilling. The Egilabria-1 drill target was a robust, seismically defined, gas/condensate prone target. Other features of the Egilabria structure were:

1. Its favourable flank position relative to the basin depocentre.

2. The down cutting into the basin of the structural trend to the west creating an ideal conduit for hydrocarbon migration and concentration.

3. The early development of the initial structure evidenced by the reversal of a probable syndepositional down-to-the-north normal fault.

4. Flats events near the spill point of the structure were present on a number of seismic sections. These are interpreted to be a fossil direct hydrocarbon indication on the basis of the drilling results.

Egilabria-1 was proven closed on the base of Mesozoic, plus seismic horizons A, B, C and probably D levels. Dip closure was evident on the E level but strike closure was almost certainly fault dependent. Stratigraphic events between the picked unconformities A through F parallel the picked levels over the structure and were also closed. Evidence of late movement on the structure can be inferred from the closure evident through the Mesozoic section however, compactional drape could also have been responsible. The position of this structure within the basin was excellent in terms of entrapment geometry. The lack of detailed stratigraphic information for the area meant it was impossible to predict reservoir within the section.

Timing at Egilabria was very favourable with obvious down-to-north normal faults exhibiting later thrust reversal. Such early structuring implies that hydrocarbon entrapment geometries in the form of normal fault roll-overs probably existed since the time of initial basin compaction. The structure is closed throughout the foreland sequence and down to the top of the platform carbonates and this provided a robust test over a large stratigraphic section.

Desert Creek-1, the second ranked structure, was sited primarily on a fault dependant anticline on the south side of the Egilabria Fault with closure in the lower foreland sequence and the platform carbonates. It was the largest of the defined targets.

Argyle Creek-1, the third ranked target, was sited on a shallow less thermally mature closure on the platform carbonates with poorly imaged shallow seismic data. This target developed as a high block on the Egilabria Fault with a possible palaeokarst weathering surface draped by faulted and fractured foreland basin fine grained clastic rocks.

Argyle East Prospect (not drilled) comprised a small roll over anticline on the north side of the Egilabria Fault. It is closed on a number of seismic horizons within the foreland clastic sequence but not at the level of the main carbonate play.

Aerial photograph mapping and outcrop inspection confirmed Connolly Valley Prospect (not drilled) to be the core of an east-northeast trending anticline with a number of identifiable culminations. A seismic grid was recorded over two culminations, but only very poor quality data was obtained from the survey.

The Connolly Valley grid was an attempt to fast track a drill target by proving closure continuity at depth beneath a surface and aerial photograph defined anticline. Minimum extra seismic kilometres were required (approximately 30 km). Connolly Valley is an elusive target. It was not confirmed by seismic prospecting, but also may not be well placed in relation to the basin hinge line.

It appears to have been breached by faulting and is certainly quite shallow with less than 1500 m to basement.

Based on the seismic data, the biggest plays in the basin are the stratigraphic pinchouts along the northern margin, just to the south of Connolly Valley and east of Doomadgee. Pursuit of this type of trap is almost impossible with the current level of lithostratigraphic and seismic control, but the geometry observed will remain a tantalising possibility for the future, despite the poor petroleum potential confirmed by the initial drilling.

A number of possible structural leads also exist for follow-up seismic evaluation of and definition of drill targets within the basin. A range of formation times, maturities and geographic settings remain to be tested but the great promise of the basin was largely disproved by the 1992 drilling.

APPENDIX 4

Metal exploration geophysics and geochemistry in the Mount Isa Basin

Corbett (1990) described an overview of geophysical techniques applied to gold exploration in the Great Basin of Nevada. All of the techniques described have been used in the Mount Isa Basin to achieve a range of objectives including direct detection of mineral occurrences.

Taylor and Scott (1992) described the evaluation of gossans in relation to lead-zinc mineralisation throughout the Mount Isa region. The various types of gossans developed over different mineralisation styles exhibit a range of physical and chemical characteristics. Many of the major mineral deposits of the Mount Isa Basin have characteristic gossans, however the time for discovery of surface mineralisation in the basin has largely passed (despite the situation at Century where surface geochemistry provided the initial drilling target).

Mr M. Barlow pers. comm. (1991) considered electrical techniques to be very successful in delineating concealed massive sulphides. Massive sulphide bodies are conductive or polarisable depending upon mineral composition, zonation and percentage of sulphide ores (particularly pyritic sulphides). Furthermore most sulphide deposits, including the stratiform deposits of northern Australia are associated with large zones of disseminated and remobilised ore that may be polarisable.

Peacock and King (1985) reported on the detection of mineralised shale over the deeper part of the HYC deposit using central loop TEM soundings. The target depth was 283 m but they estimated that a similar deposit in this geological environment could be detected at up to 500 m depth. Of course the deposit had already been identified and transmitter loop coupling to the ore body could be optimised. In a frontier exploration area the search for deep sulphide deposits would only be practical in an area in the order of km^2, using ground TEM configurations. For this case where no surficial expression is expected a detailed basin evaluation is essential and seismic analysis is therefore imperative. Airborne TEM would increase practical coverage but the target depth becomes limited to 250 - 300 metres at maximum.

Anderson and Logan (1992) defined the Osborne copper-gold deposit near Mount Isa using fixed and moving loop TEM surveys. Brescianini et al. (1992) used TEM and magnetics to define the Eloise copper-gold deposit combined with gravity and dipole-dipole IP to further characterise the deposit's response.

Isles et al. (1987) used geophysical techniques to detect similar stratiform zinc/lead deposits in Western Australia. While the targets were known to have strong chargeability, IP surveys were limited to their sensitivity of deep mineralisation due to a blanketing cover of lower resistivity basinal facies. This is a common problem in Australia where surface cover is often deeply weathered (10 - 100 m).

Isles et al. (1987) also reported on the success of gravity work in mapping host sequences, but added that for deeper and more complex geological problems seismic reflection is required for resolution.

The geophysical responses of several major deposits in the Mount Isa and McArthur Basins were described by Fallon and Busutti (1992) discussing Mount Isa, Thomas et al. (1992) reviewing Century, and Shalley and Harvey (1992) covering HYC. IP techniques clearly provided the most convincing definition.

Parnell (1992) described metal enrichment in bitumens from Carboniferous-hosted ore deposits of the British Isles and suggested that the metal geochemistry of bitumens may be of value in ore exploration. The most abundant and/or widest range of inclusions are found in bitumens from the most substantial ore deposits provided the bitumens were in contact with the hydrothermal ore-bearing solutions. Additionally there is also a general trend of increasing abundance of inclusions with decreasing H/C ratio due to increasing maturity. This latter feature is also observed in the northern Mount Isa Basin.

Monson and Parnell (1992) described the anomalous association of light hydrocarbon gases with the rocks in which mineralisation occurs in the Carboniferous rocks of Ireland, an intriguing analogue for the northern Mount Isa Basin.

Metallic geochemical investigations have long been used to delineate Mississippi Valley lead-zinc deposits in the USA (e.g. Barnes and Lavery, 1977; de Geoffroy and Wu, 1970). In the McArthur Basin, Lambert and Scott (1973) described in detail the geochemical halo of the host lithologies around the HYC deposit based on numerous drillhole intersections. Enrichment of zinc, lead, arsenic and mercury was reported in association with high iron and manganese dolomites plus vitroclastic tuffite bands. The latter probably reflect the physical depositional environment rather than any geochemical ore association.

APPENDIX 5

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